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OVER-THE-AIR SYNCHRONIZATION OF MICROCELLULAR WIRELESS SYSTEMS

BY

Amitabh Mathur ©

A Thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirement for the degree of Master of Science

DEPARTMENT OF ELECTRICAL ENGINEERING

Edmonton, Alberta

Fall 1994

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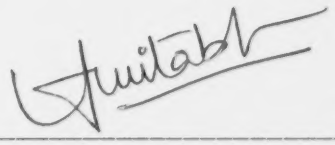

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The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Over-the-Air Synchronization of Microcellular Wireless Systems** submitted by **Amitabh Mathur** in partial fulfillment of the requirements for the degree of **Master of Science.**

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Colin Englefield

7 October 1994

in memory of my father

Abstract

Synchronization of base stations is crucial for the second generation digital cellular systems which operate in the Time Division Multiple Access/Time Division Duplex (TDMA/TDD) mode. Traditionally the base stations are synchronized by some centralized scheme involving either a common beacon from a master base station, or synchronization through a wireline network. To overcome drawbacks of these centralized methods, a new approach of over-the-air synchronization of base stations in a digital cellular system has been proposed recently. This is a relatively decentralized approach as it involves no common synchronization signal and the base stations synchronize themselves by deriving the timing information from the signals transmitted by other base stations in the system. A computer simulation model of TDMA-TDD cellular system has been set up to evaluate the performance of this algorithm. The model is based on the DECT (Digital European Cordless Telecommunications) standards. The performance of synchronization schemes has been evaluated in the indoor environment. Some variations of the proposed method are also analyzed. The robustness of the system against hostile signal propagation conditions, and some of the other possible factors which can affect the system, is established from the simulations.

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List of Abbreviations

BER	Bit Error Rate
CDMA	Code Division Multiple Access
DCA	Dynamic Channel Allocation
DECT	Digital European Cordless Telecommunication
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
GMSK	Gaussian Minimum Shift Keying
GPS	Global Positioning System
MCHO	Mobile Controlled Hand-Off
MSK	Minimum Shift Keying
NRZ	Non-Return-Zero
RSSI	Received Signal Strength Indicator
S/I	Signal to Interference
TDD	Time Division Duplex
TDM	Time Division Multiplex
TDMA	Time Division Multiple Access

List of Symbols

$T_i(t)$	Timing of base station i
$T'_i(t)$	Received Timing of Base Station i
$\Delta' T_{ij}$	Measured Timing Error Between Base Stations i and j
ΔT_{ij}	Calculated Timing Errors Between Base Stations i and j
ΔE_i,	Average Timing Error at Base Station i
P_j	Power of Signal from Base Station j
t_o	Propagation Delay Constant
ε	Gain Constant for Iteration Process
H	Hierarchical Value of a Base Station
H_{min}	Minimum Hierarchical Value
L_m	Total Path Loss
L_l	Linear Attenuation Factor
d	Distance between two base stations
d_l	Distance at which Linear Attenuation Starts
λ	Wavelength of the Signal
F	Number of Floors
W	Number of Walls
p	Attenuation due to a Wall
k	Attenuation due to a Floor
d	Distance between two Base Stations
c(t)	Input Data Stream
a_n	Binary Data
T	Bit Period
B_t	3 dB cutoff frequency of the Gaussian filter
H(f)	Transfer Function of Gaussian Filter

$h(t)$	Impulse Response of Gaussian Filter
$g(t)$	Gaussian Pulse
$erf(y)$	Error Function
$S(t)$	Output of GMSK Modulator
f_d	Maximum Frequency Deviation
$\Phi_S(t)$	Change in the Phase of the RF Carrier due to Modulation
h	Modulation Index
$R(t)$	Envelope of the Received Signal
σ	Standard Deviation of the Timings
$\bar{t}$	Mean of the timings

Chapter 1

Introduction

1.1 Mobile Radio Communication

The ultimate technological vision for mobile radio communication has been around for years: individuals carrying small, inexpensive handheld communicators and being reached by voice or data with a single phone number - no matter where they are. No separate numbers for office, home, pager, facsimile, or car. No more being out of touch on public transportation, away from the office, or on a city street. Although we may still be a long way from this advanced level of wireless communication, clearly we are moving steadily towards it.

The provision of a wider range of sophisticated services to mobile users is becoming increasingly important. While voice communication will likely remain the dominant service offering for many years to come, the demand for more advanced services such as video and data is steadily growing. The demand for cellular telephones has soared since their introduction in 1983. At the beginning of 1993, there were more than 10 million cellular telephone customers in the United States and another 9500 were being added each day. Studies suggest that by the end of 1995 the number of subscribers will reach 30 million [1]. It is also expected that more than 50 percent of the telecommunication traffic will be associated with cordless or mobile terminals by the year 2000 [2].

Like most expanding areas of endeavor, mobile radio communication has been explored for some time. However, this exploration is now entering the stage of rapid growth which is stimulated largely by the fact that in certain regions demand is becoming comparable to the maximum capacity of the currently available mobile systems. Traffic estimates show a peak traffic requirement for city centers of 500 Erlangs per sq. km outdoors and above 5000 Erlangs per sq. km indoors [3]. Therefore, if the next generation of mobile telecommunication system is to satisfy the market demand, it has to offer a greatly improved traffic capacity within the limited radio spectrum.

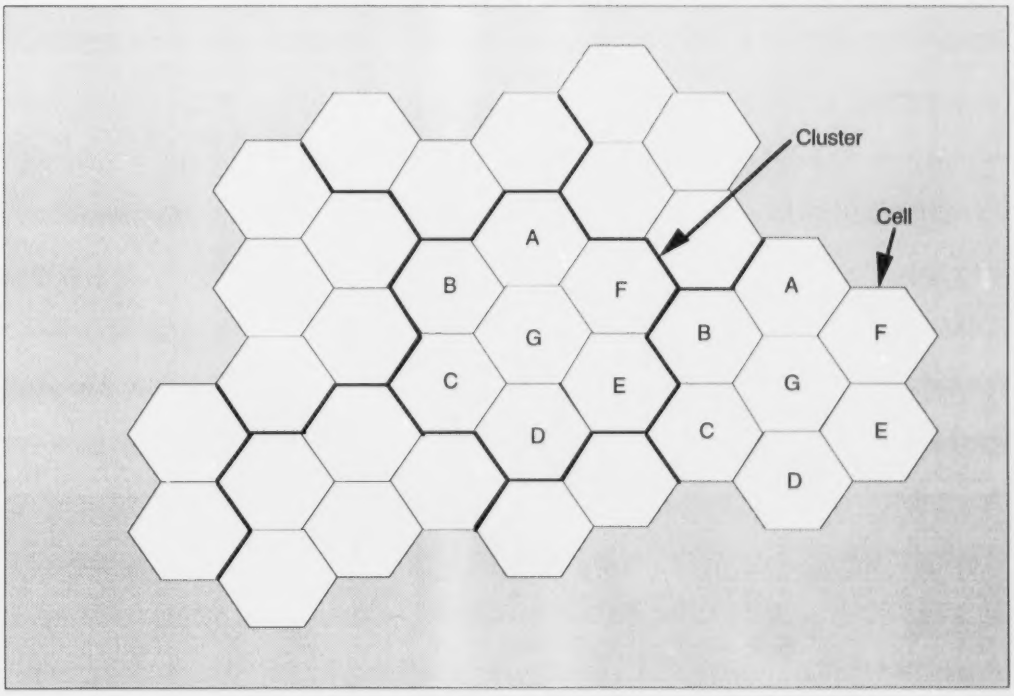

Figure 1.1 Cellular System

Cellular system operation relies on frequency reuse. The service area is divided into a number of cells and each cell has a base station which communicates with portables within its region. The cells are grouped into

clusters as shown in Figure 1.1. The allocated spectrum is distributed amongst the cells of a cluster. The clusters are repeated to achieve frequency reuse. In a cellular system larger cells can be split into smaller cells so that the same area has more cells; this leads to increased frequency reuse and thus a greater system capacity. Thus, cell splitting appears to be a suitable way to solve the capacity problem of radio communication in dense areas such as a city center and some motor ways. However, as the cell size decreases, the number of base stations in the service area must increase which increases system complexity. Beyond a certain limit, cell splitting is not economically viable. The present analog systems have already been saturated in many metropolitan areas. Therefore, attempts have been made to investigate other approaches which in conjunction with cell splitting would improve the capacity of the system.

1.2 Digital Cellular Systems

One of the most promising approaches is to use the available spectrum more efficiently. Digital technologies used in the second generation cellular systems are spectrally more efficient than their analog predecessors. There are a number of other reasons too for adoption of digital systems like robustness, adaptiveness, fewer radios etc..

Two distinct multiple access methods can be used in conjunction with the digital transmission technologies. Time division multiple access (TDMA) and code division multiple access (CDMA). In TDMA, the communication signal of each user is compressed in time, enabling possible multiple transmissions on the same frequency. In CDMA a number of users share the same spectrum

without interference by employing a unique code sequence to distinguish each transmission.

Although the relative merits of these approaches to multiple access are still debated, the TDMA technology has been adopted (at least partially) in the three major markets (USA, Europe and Japan). The Pan-European Digital Cellular System (GSM), the North American Digital Cellular System (IS-54), the Japanese Digital Cellular System, and Digital European Cordless Telecommunications (DECT) are all TDMA systems.

1.3 Time Division Multiple Access (TDMA)

The term "multiple access" refers principally to the fact that a large number of portables share common resources by occupying a channel when required. The TDMA systems cited above are actually hybrid systems; they are combination time division multiple access (TDMA) and frequency division multiple access (FDMA). As shown in Figure 1.2, the available spectrum is divided into a number of relatively narrow radio channels, centered about their carrier frequencies. The signal on every carrier frequency is divided into fixed time frames. Each time frame is further divided into a number of time slots. The signal is transmitted in discrete signal bursts over the duration of a time slot. In a TDMA cellular system each participating portable transmits one or more traffic bursts, synchronized so that they occupy assigned non-overlapping time slots in a TDMA frame. The base station transmits the signal for different portables in different time slots of the frame and the portables are timed such that they receive the signal in their respective assigned time slots.

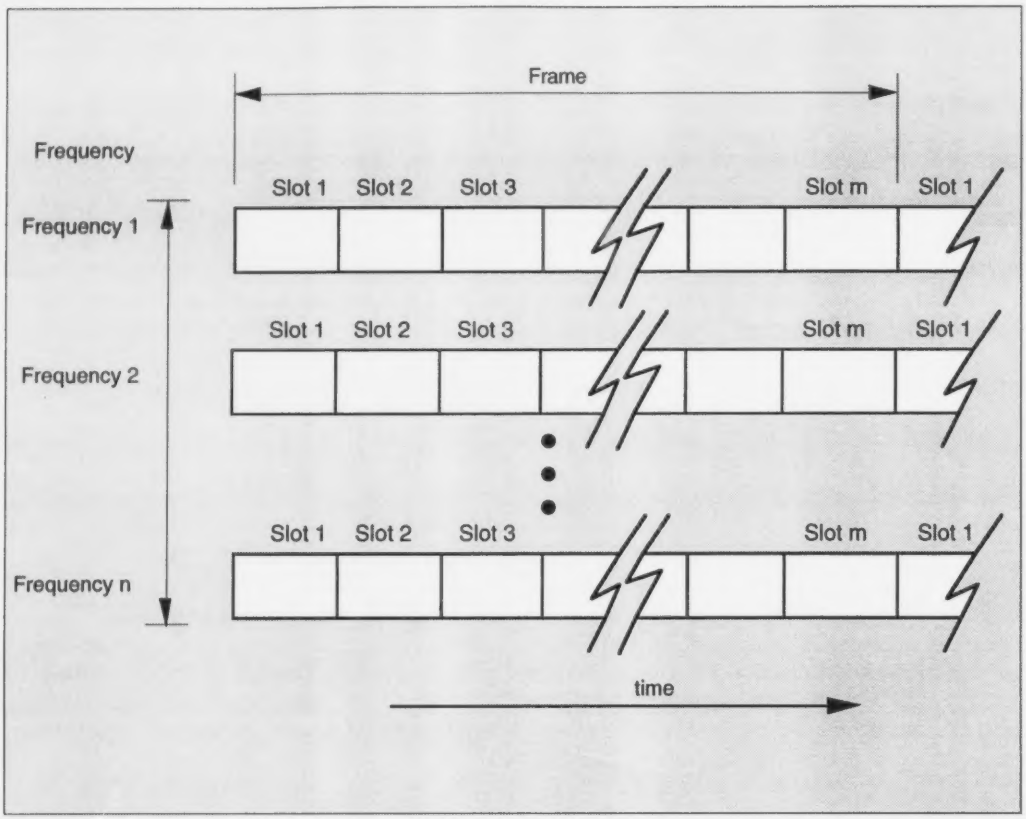

Figure 1.2 TDMA Time-Frequency Matrix

Wireless links normally have to support simultaneous two-directional (duplex) transmissions i.e. from base station to portable and portable to base station. There are two possible ways of achieving duplex transmission in radio systems; Time Division Duplex (TDD) and Frequency Division Duplex (FDD). Both of these duplexing techniques are used in different TDMA systems. For example, North American Digital Cellular (IS-54) is a TDMA-FDD system, and DECT is a TDMA-TDD system.

1.3.1 TDMA-FDD System (IS-54)

The North American digital (dual mode) IS-54 system is a TDMA-FDD system. FDD requires paired carriers for the forward and the reverse link, i.e. the carrier used for transmission from base station to portable is different from the carrier used for the transmission from portable to base station. This system operates within a 50 MHz bandwidth in the 800 to 900 MHz frequency range [4].

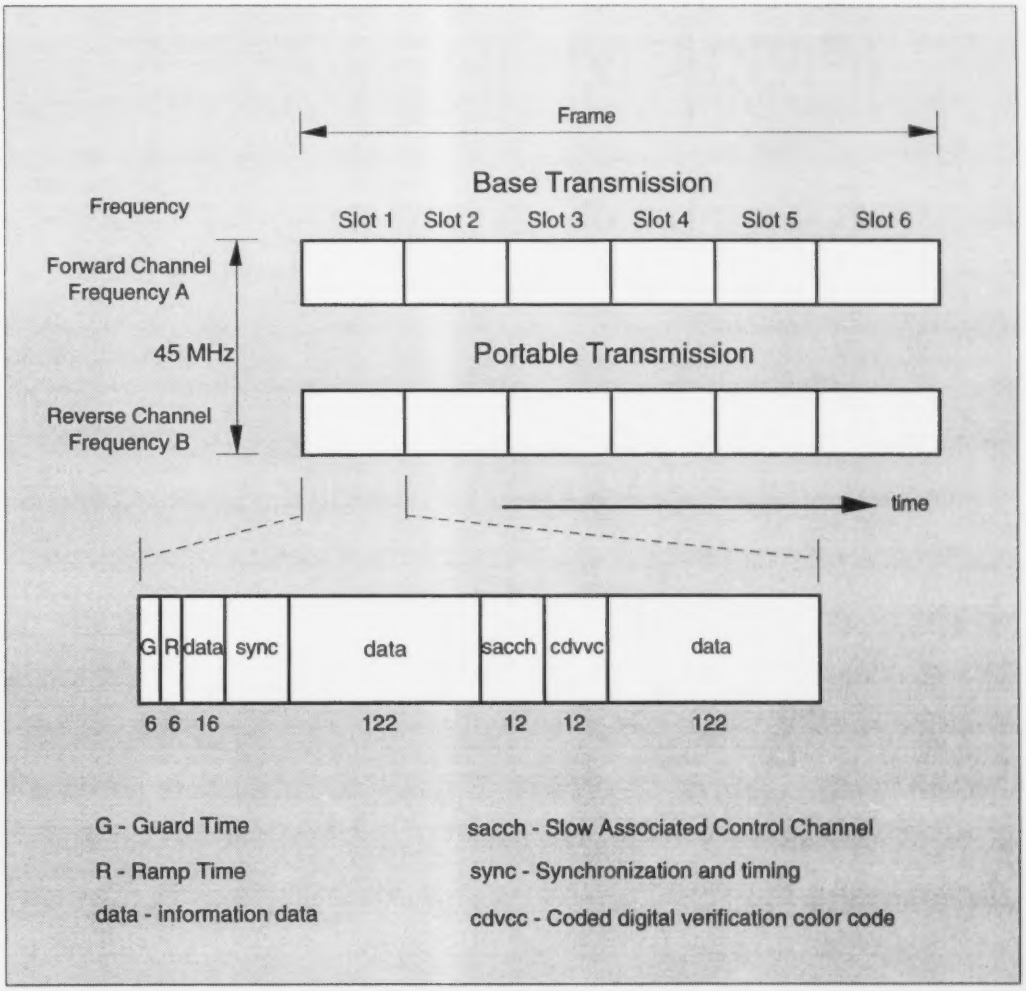

Figure 1.3 IS-54 Frame Structure

The total bandwidth is divided into a 25 MHz base station transmit band and 25 MHz portable transmit band. Each of these is bands is further divided into two subbands so as to allocate them to the different operators. The total bandwidth is divided into 832 two way carriers; 416 for each operator. Each link consists of two carrier frequencies having bandwidth of 30 kHz each. The frame length of each digital TDMA channel is 40 ms. Each frame has six identical time slots. A EIA/TIA standard TDMA frame is shown in the Figure 1.3. The position and the duration of each burst in the TDMA frame is assigned according to a protocol established for the network.

1.3.2 TDMA-TDD System (DECT)

The DECT system operates in a TDMA-TDD mode. In a TDD system the same carrier frequency is used for transmission in both directions (from portable to base station and vice versa). This eliminates the need for paired subbands for forward and reverse link transmission. Each frame is divided into two parts, half of it is for transmission from base station to portables (forward link) and the other half is for transmission from portables to base station (reverse link). The transmissions in opposite directions occur in evenly spaced time slots of a frame (i.e. separated by half a TDMA frame). The disadvantage of this method is that a guard time is required between the forward and reverse link transmissions which is proportional to the cell size. So, TDD is generally suitable for micro cellular outdoor and indoor environments where the cell size is small. The TDMA-TDD frame structure adopted by DECT is shown in Figure 1.4 [5]. Each frame has 24 slots, the first 12 slots are for the forward link and the remaining 12 slots are for the reverse link.

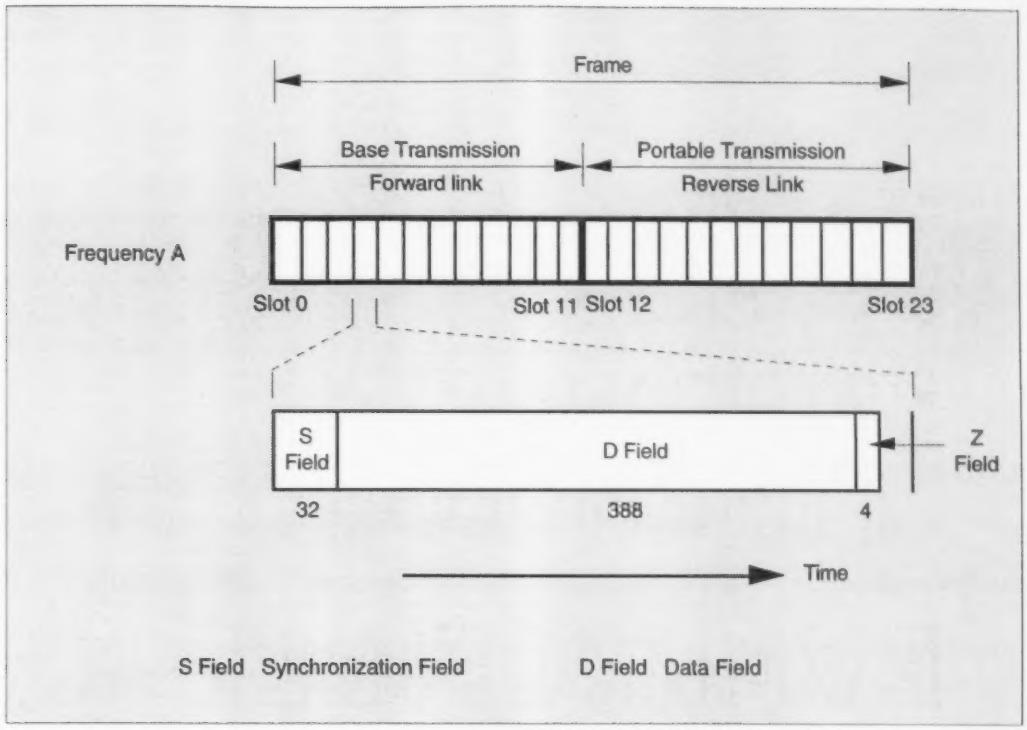

Figure 1.4 DECT Frame Structure

1.4 Synchronization of Base Stations

One of the problems in the implementation of TDMA in cellular systems is synchronization of the base stations. Synchronization of the base station implies that all the base stations in the system should be timed such that their frames are aligned as illustrated in Figure 1.5. The portables extract their timing information from the base stations with which they are communicating. So a portable is always synchronized to the base station. However, the base stations in a system may or may not always be synchronized with each other. The synchronization of base stations means that the frame timings of the base stations coincide with one another, i.e. all of the base stations transmit the first bit of the first time slot of their frame at the same time instant.

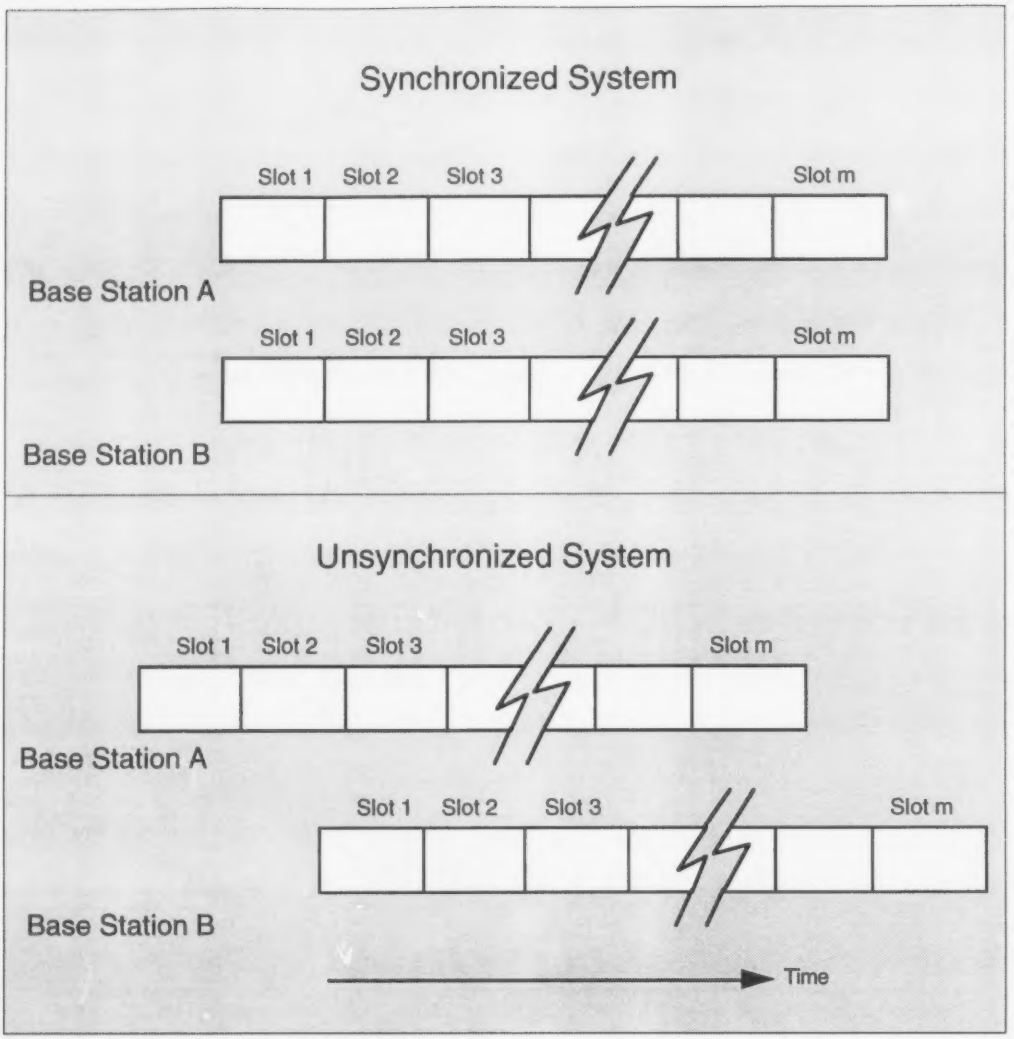

Figure 1.5 Synchronization of Base Stations

A typical wireless access network is shown in Figure 1.6. The base stations are connected to the Public Switched Telephone Network (PSTN) through wireless controllers. There are digital links between the base stations and the PSTN. At each base station the clock is derived from the received digital signal. Therefore all the base stations in the network have the same

clock. Although, there is a common clock at all the base stations in the system, the frame timings are adjusted individually at all the base stations.

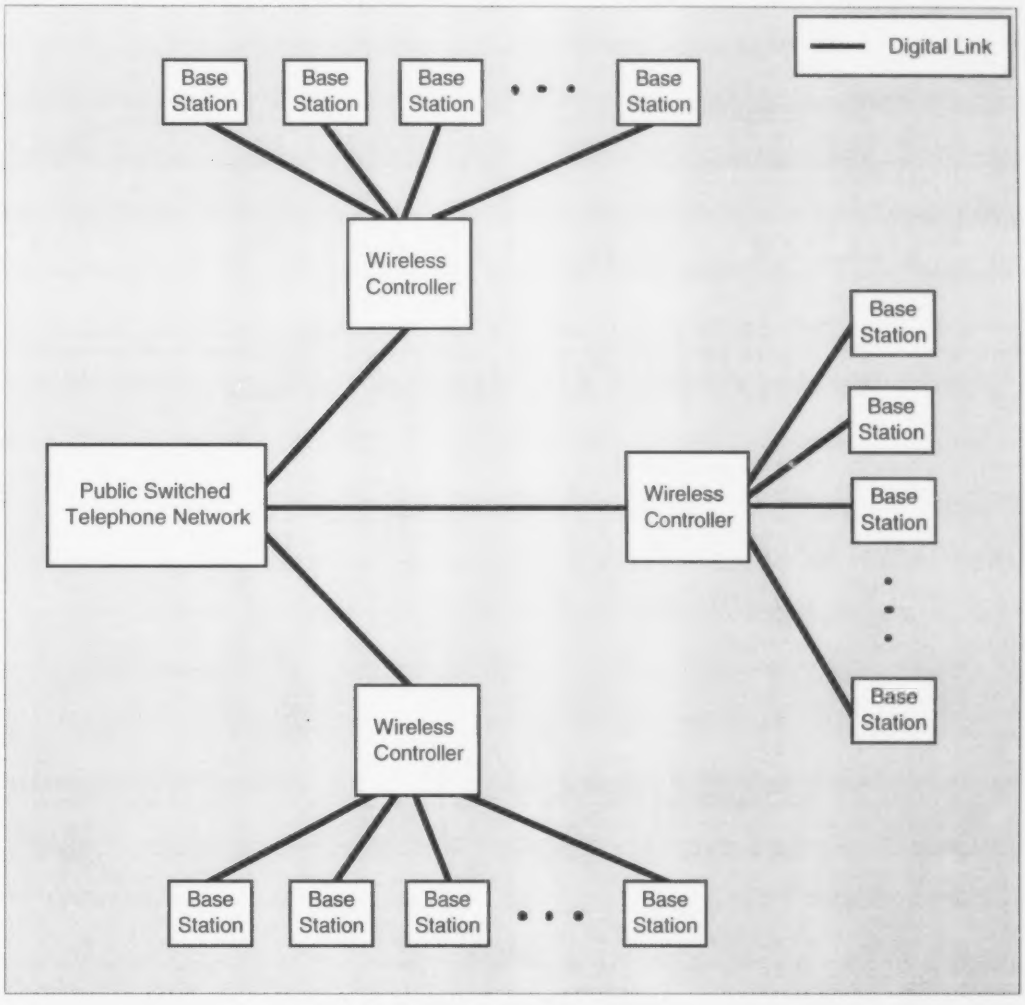

Figure 1.6 Digital Cellular Network

1.5 Effects of Synchronization on System Performance

In this section the most significant detrimental effects due to imperfect synchronization of base stations, such as the effect on signal to interference

ratio, the effect on channel allocation, and the effect on the hand-off, are discussed.

1.5.1 Effect on Signal to Interference (S/I) ratio

Cellular systems are interference limited systems. Broadly speaking there are two types of interferences; co-channel interference and adjacent channel interference.

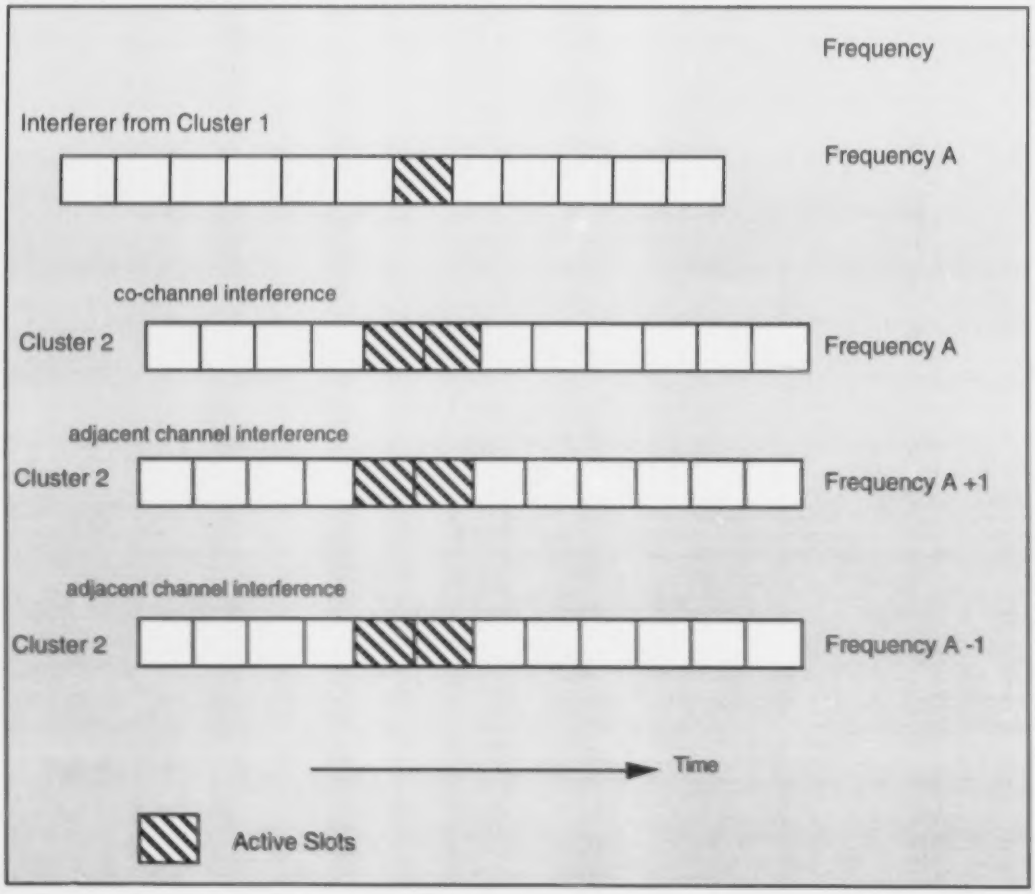

Figure 1.7 Interference in an Unsynchronized TDMA system

In a TDMA system, if two systems are synchronized, one traffic channel in the system would be a co-channel interferer to one traffic channel in the other system, and an adjacent channel interferer to two traffic channels.
But, as shown in Figure 1.7, if the systems are not synchronized one traffic channel could be a co-channel interferer to two traffic channels in the other system, and an adjacent channel interferer to four traffic channels. Imperfect synchronization affects TDMA-FDD and TDMA-TDD systems differently, which is discussed in this section.

1.5.1.1 Effect on TDMA-FDD System

In TDMA-FDD systems the forward and reverse links are on different carrier frequencies so the forward links get interference only from the other forward links and the reverse links get interference only from the other reverse links. In TDMA-FDD systems there could be two modes of transmission from the base stations:

1. Base stations transmit continuously in every slot of the frame whether there is traffic in all of the slots or not. This is referred to as TDM (time division multiplexing).

2. Base stations transmit only during the active slots. This is referred to as TDMA (Time Division Multiple Access). This approach reduces the co-channel interference, because usually each frame has some idle time slots and there is no signal transmitted during these intervals.

In TDM systems since the signal is always transmitted from the base station whether there is traffic for all the slots or not, there would be no additional interference in the forward link due to the misalignment of the frames. But in a TDMA system, since a base station transmits only during the active time slots there could be some additional interference in the forward link due to asynchronism. However, in both the cases the reverse link is TDMA, hence the asynchronism would cause some additional interference in the reverse link. As shown in Figure 1.8, if the system is not synchronized there is a relative time slip between the TDMA frames transmitted from different base stations.

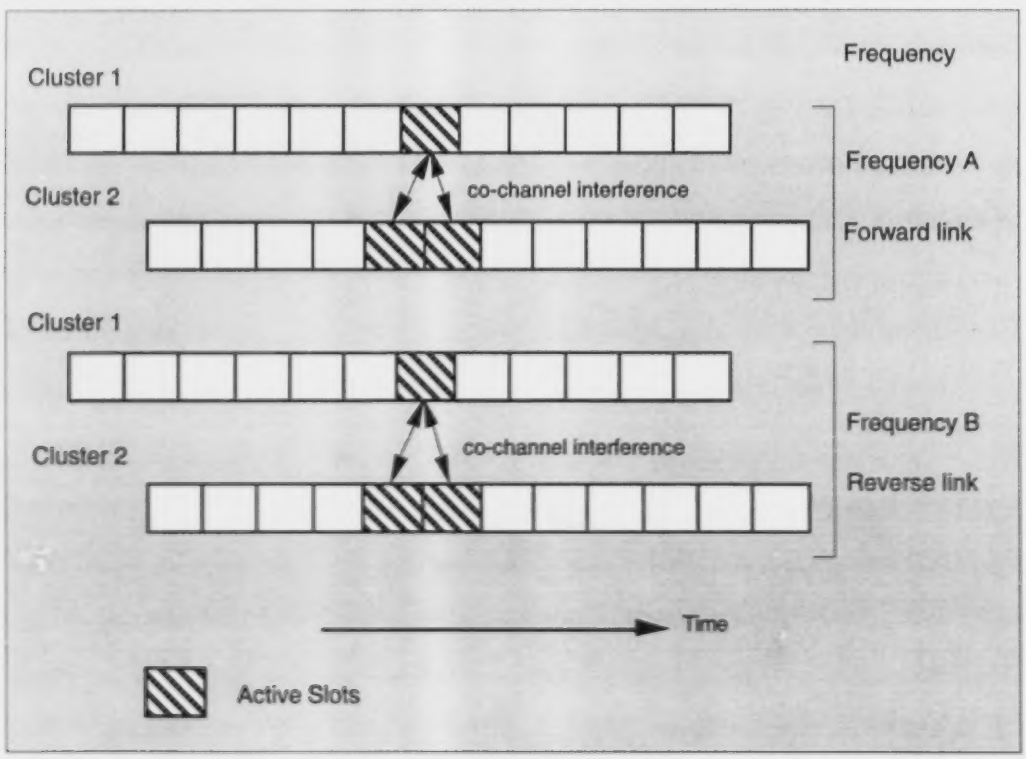

Figure 1.8 Co-channel Interference in an Unsynchronized TDMA-FDD System

So, one active traffic channel on one carrier frequency could be a co-channel interferer to two active traffic channels on the same carrier frequency in

a different cluster. If the frames were synchronized, it would have caused interference to only one slot.

Thus, imperfect synchronization increases the probability of co-channel interference. In TDMA-FDD systems the slot level synchronization is important to control interference. However, frame level synchronization is required for hand-over and encryption.

1.5.1.2 Effect on TDMA-TDD System

In TDMA-TDD systems frame level synchronization is crucial. In a synchronized TDMA-TDD system during the forward link transmission, portables receive co-channel and adjacent channel interference from other base stations and during the reverse link transmission the base stations receive co-channel and adjacent channel interference from other portables.

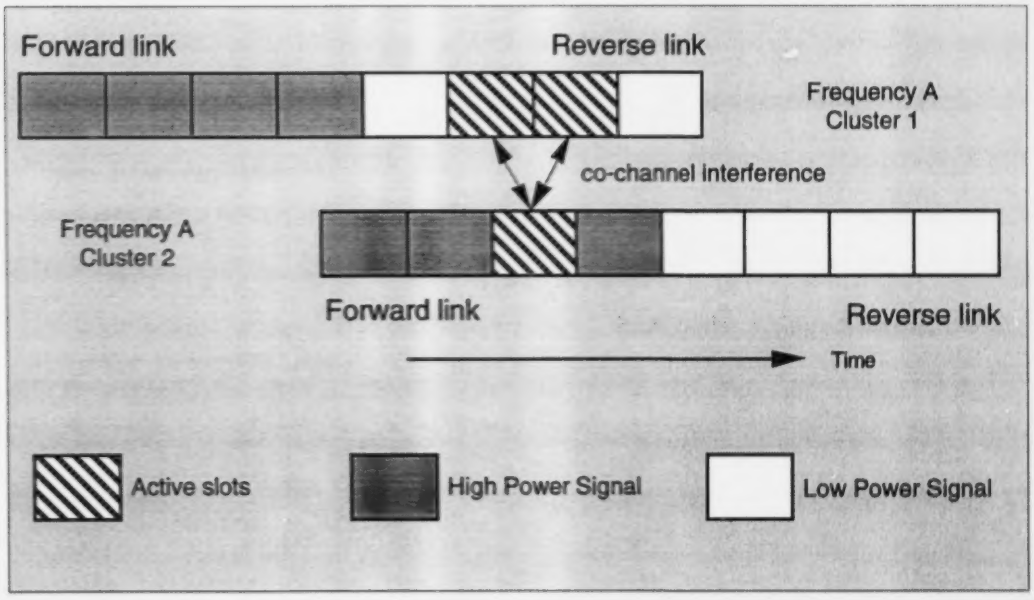

Figure 1.9 Co-channel interference in an Unsynchronized TDMA-TDD System

But if the base stations are not synchronized there is an interference between forward link and reverse link transmissions as shown in Figure 1.9, i.e. during the reverse link transmissions a base station which normally receives interference from portables may receive co-channel and adjacent channel interference from other base stations and vice versa.

This additional interference by co-channel forward links becomes very significant if the base station antennas are set higher than those of portables to obtain better coverage or if the base station transmission power is set higher than that of portables to offset the likely lower sensitivity of portable receivers. As a result, the reverse link of the TDD based system will be severely degraded if the base stations are not synchronized.

In a TDMA-TDD system deterioration of the signal quality due to interference depends on the difference in the power of the signals transmitted by the base station and the portable, the timing offset between the frames transmitted by the different base stations, and the volume of the traffic. In a TDMA-TDD system the reverse link SIR deteriorates by 18.2 dB and the forward link SIR improves by 0.9 dB, if the base station/portable power difference is 20 dB, the system is 60% occupied, and the timing offset between the frames is half the frame length i.e. the worst case asynchronism occurs [6].

1.5.2 Effect on Channel Allocation

In an environment of very heavy traffic with an uneven distribution, a channel allocation method which assigns the channels dynamically based on the traffic and the S/I ratio would prove to be more efficient than the fixed frequency assignment per cell. The DECT system uses dynamic channel

allocation (DCA). A simplified description of the procedure for call setup and channel allocation is as follows [7].

1. The portable measures the signal strength from all the base stations and locks on to the strongest.
2. The portable measures the signal strength on all the slots and maintains a list of the quietest slots.
3. When a paging message is received by a portable or a portable initiates a call, the portable sends an Access Request message on the quietest slot in the list.
4. If the base station receives the Access Request message and is free to use this slot, it returns an Access Granted message.
5. When the portable receives an Access Granted message on the selected slot, it returns an Access Confirmation message and the call begins.
6. However, if the portable does not receive an Access Granted message the setup fails for this slot. The portable then tries again, this time using the next quietest slot and so on. After a number of slots have been tried without success, the call setup is terminated.

Channel allocation is based on the short term interference situation. As described in section 1.5.1 asynchronism can increase co-channel interference. This co-channel interference makes it more difficult for the portable to find a "free" channel. Thus the available traffic capacity may be reduced.

1.5.3 Effect of Synchronization on Hand-Off

For call hand-off digital systems use the mobile controlled hand-off (MCHO) or mobile assisted hand-off (MAHO) strategies[8]. In these strategies

both the portable and the base station monitor the signal quality of their respective channels. Both RSSI and free channel S/I measurements on the alternative channels are done by the portable. If the signal of another base station is stronger than that of the current base station by some threshold value, or the communication quality becomes too poor, the hand-off procedure is initiated. In many systems the procedure for the hand-off is identical to the call setup except that the portable continues communicating with the old base station until a new connection has been made. Also, the call is not dropped after a number of attempts; instead the portable waits for some time and then tries again.

Synchronization at the frame and subframe level is essential for the hand-off and for the scanning procedure for the selection of a free channel. The portable makes the measurements on the alternate channels and a portable can not synchronize to more than one base station at a time. Therefore, if the base stations are not synchronized the portable will not be able to make the measurements on the alternate channels.

The increased interference caused by asynchronism can also result in an increased hand-off frequency. As noted in Section 1.5.1.1. unsynchronized operation can increase the interference level, particularly for the reverse link. If a particular channel assignment leads to higher interference (lower S/I ratio) in an already active slot in a different cell, an inter-cell or intra-cell hand-off may become necessary due to the reduced S/I ratio.

The higher interference due to asynchronism in the system could adversely affect the hand-off mechanism in the system. During hand-off the

system looks for an unused or free channel as explained earlier. There is a possibility that some channels are not selected as free because of the higher interference due to unsynchronized operation. Hence, this can lead to capacity loss or even call dropping.

1.6 Thesis Overview

Chapter 2 describes the different synchronization techniques which have been evaluated in this thesis. Chapter 3 describes the computer simulation model developed for this thesis. Chapter 4 presents the results obtained in the project and their interpretation. Chapter 5 concludes the thesis with a summary of the results and suggests areas of possible future research.

Chapter 2

Over-the-Air Synchronization

2.1 Synchronization Techniques

The most common approach to synchronization of base stations is to use a common timing reference that is made available to each base station. This reference usually comes from a master base station or the Mobile Telephone Switching Office (MTSO)/Wireless Controller, either through a common synchronization beacon or as a synchronization signal on the wireline network.

2.1.1 Common Beacon

Conceptually, the simplest way to synchronize a population of base stations is to permanently broadcast a synchronization timing signal from a central station over a wide geographical area. In this method each station gets an external time reference. For cellular system where base stations are distributed over a wide area, this centralized synchronization approach has some practical limitations. Firstly, transmitter of the timing signal must be high power for large systems. Secondly, we would need a separate receiver at all the base stations and a separate RF carrier for this timing signal which would not be available to any of the clusters. So, there will be some waste of the available spectrum. If the reference time is made available from a satellite then at each base station we would need a GPS (Global Positioning System) receiver, which may be questionable economically.

2.1.2 Wireline Synchronization

For synchronization of wireless systems the wireline network may also be used. For example, in the DECT standard there is provision for the synchronization of base stations by an additional wireline network using 'DECT Synchronization ports'. An alternative is a hybrid approach. Timing of a number of wireless controller is synchronized by the Global Positioning System (GPS) or a common beacon. The base stations associated with each controller are synchronized by a wireline network. The timing of all the base stations is synchronized to the timing of the controller or to a master base station by a TDMA frame synchronization pulse which is sent to all the other base stations associated with an individual controller. But, this approach would require an additional infrastructure.

2.1.3 Over-the-Air Synchronization

The synchronization techniques explained above are inherently centralized i.e. the synchronization is done from a master base station or MTSO. Recently, a new decentralized synchronization technique has been proposed in which the control of synchronization is performed, as far as possible, at each base station [9]. At every base station the timing is adjusted according to a synchronization algorithm until all the base stations are mutually synchronized. Different variants of over-the-air synchronization are explained in detail in the next section.

2.2 Over-the-Air Synchronization Methods

In over-the-air synchronization each base station monitors signals transmitted by the other base stations in the system, to measure their frame timings and power levels. From this information a base station updates its timing. This process is performed at every base station until all the base stations are synchronized. The process of updating of timing is outlined as follows:

Step 1. Measurement of timing errors.

Step 2. Calculation of average timing error.

Step 3. Adjustment of timing of the base station.

These three steps involved in updating the timing at a base station in over-the-air synchronization are explained in detail in the following section.

Step 1 Measurement of Timing Errors

In TDMA each frame has a number of time slots. Each slot has some synchronization/timing bits to mark its relative position in the frame. The *timing* of a base station is defined as the position of the timing markers of the first slot in the frame, within a window containing the frame. For example the DECT system has a TDMA-TDD structure, each frame has 24 time slots, which are numbered from k = 0 to 23, and the first 32 bits in each slot are synchronization bits as shown in Figure 1.4. The frame timing is determined by the position of the synchronization bits of slot k=0, within a window containing the frame. The

timing error between two base stations is defined as the difference in the timings of two base stations.

Assume the timing error is being measured at base station i with respect to a base station j. The following discussion assumes measurement errors of the timing is negligible. The measured timing error $\Delta'T_{ij}$ is given by

$$\Delta'T_{ij}(t) = T'_j(t) - T_i(t) \qquad ...(2.1)$$

where $T_i(t)$ is the timing of the base station i, and $T'_j(t)$ is the received timing of base station j. The received timing of the base station j is the actual timing offset by the propagation delay.

$$T'_j(t) = T_j(t) + \text{propagation delay} \qquad ...(2.2)$$

where $T_j(t)$ is the actual timing of the base station j. To roughly compensate for the measurement error due to propagation delay, the timing error is calculated as

$$\Delta T_{ij}(t) = T'_j(t) - T_i(t) - t_o \qquad ...(2.3)$$

where t_o is a propagation delay constant, which is the estimated propagation time between the two closest base stations.

Step 2 Calculation of Average Timing Error

At each base station timing errors are measured with respect to a number of other base stations in the system. Average timing error is calculated from these timing errors. Two strategies for calculating average timing error are considered. In one approach the timing error are averaged with the received power level as a weighting factor. The average timing error at the base station i, ΔE_i, is given by

$$\Delta E_i = \frac{\sum_{j=1}^{N} P_j \Delta T_{ij}}{\sum_{j=1}^{N} P_j} \qquad ...(2.4)$$

where P_j is the power level of the received signal from base station j, ΔT_{ij} is the timing error between the receiving base station i (base station at which timing is being updated) and the source base station j (base station from which the signal is being received), and N is the number of base stations from which the timing errors are measured. This algorithm would emphasize the timing errors of the higher power signals, i.e. the errors with respect to the neighboring base stations would be heavily weighted.

The second approach used for averaging is a simplification of the first one. In this case no weighting is applied. The average error is calculated by taking the mean of the timing errors. The average timing error at base station i, ΔE_i is given by

$$\Delta E_i = \frac{\sum_{j=1}^{N} \Delta T_{ij}}{N} \qquad ...(2.5)$$

In this case the effect of distant base stations is the same as that of closer ones.

Step 3 Adjustment of timing at a Base Station

The average timing error is used to adjust the timing of the base station in question. The new timing of the base station i is given by

$$T_i(t) = T_i(t) + \varepsilon \Delta E_i \qquad ...(2.6)$$

where ε is the gain constant for the iteration process.

In this way the timings are updated at different base stations until all the base stations in the system are synchronized. The different ways in which the timings of the stations in a system can be updated are discussed in the following section.

2.2.1 Sequential Synchronization

In the sequential approach the updating of timing is done at one base station at a time. The sequential synchronization is co-ordinated by a controller, which sequentially asks one base station at a time to update timing. Therefore, at any given time only one base station updates its timing. For updating its timing, each base station turns off its transmission and monitors the signals transmitted from the other base stations in the system, one by one, and then adjusts its timing as explained in Figure 2.1.

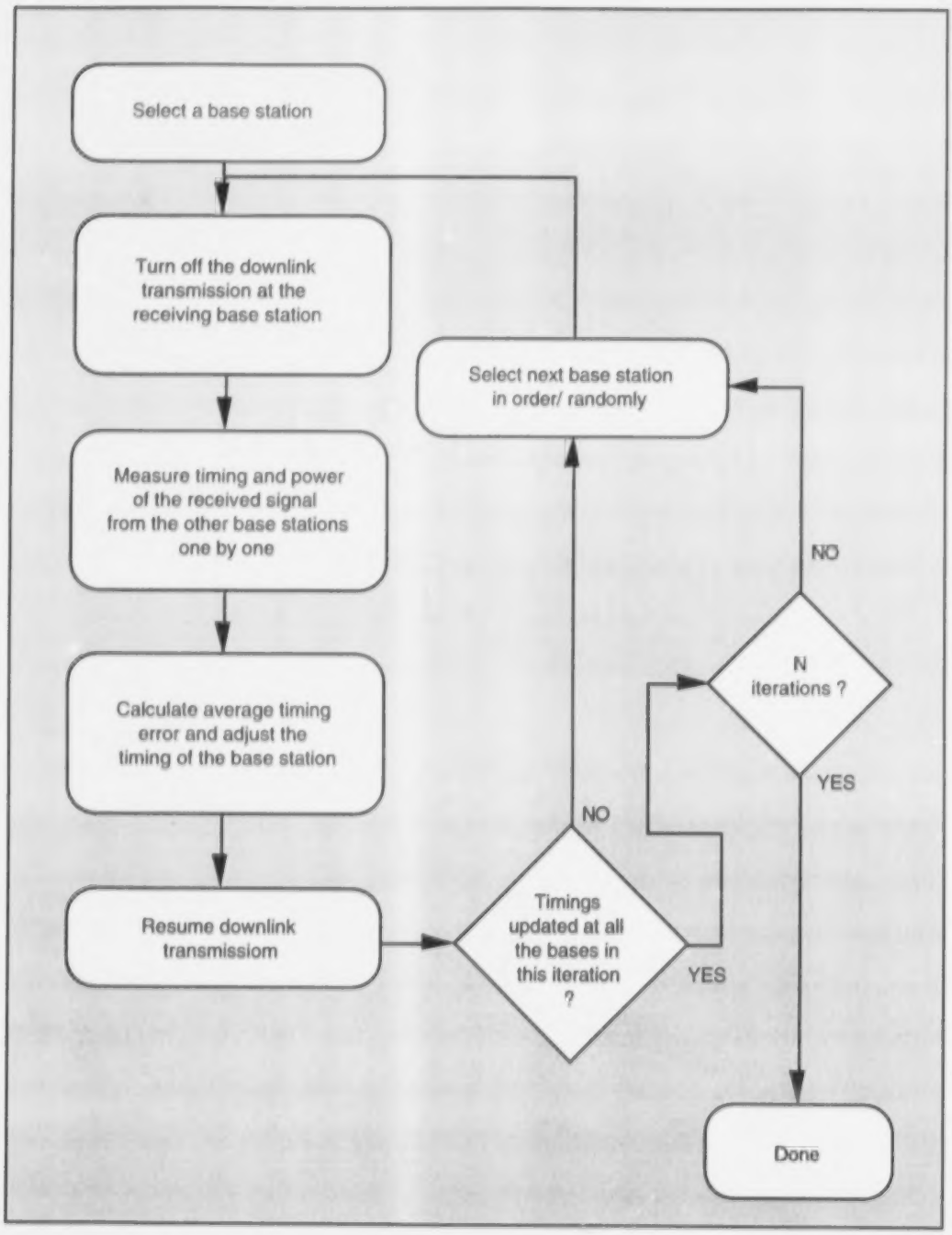
Select a base station
Turn off the downlink transmission at the receiving base station
Measure timing and power of the received signal from the other base stations one by one
Calculate average timing error and adjust the timing of the base station
Resume downlink transmissiom
Timings updated at all the bases in this iteration ?
NO
YES
Select next base station in order/ randomly
N iterations ?
NO
YES
Done

Figure 2.1 Flow Diagram for Sequential Synchronization

When there is no traffic, a base station transmits on a single slot of its frame on one carrier frequency. Different base stations in the system choose slot and frequency combination such that there in no interference. Therefore, a base station can monitor signals from the different base stations without interference.

The updating of timings at different base stations can either be done in a fixed or random order. In the fixed order approach the base stations in the system update their timings in the same fixed order in every iteration. In random updating every base station updates its timing once in every iteration, but the order in which base stations update their timings is randomly generated. So, in successive iterations the base stations update their timings in a different orders.

2.2.2 Simultaneous Timing Updating at Selected Base Stations

In the previous approach the central control unit asks one base station at a time to update its timings and the selected base station monitors signals from all other base stations in the system one by one. In the approach described in this section timings are updated simultaneously at a number of base stations as explained in Figure 2.2. Each base station monitors signals from a set of selected neighboring base stations. The central control unit has the information about which base station monitor signals from which set of base stations. Every time a base station is selected the control unit determines a set of other base stations in the system that can be simultaneously turned off such that all these selected base stations can make measurements simultaneously. Since, a base station has to turn off its own transmission while monitoring signals from other base stations, the base station are selected such that any of these selected

base station is not required for timing update by any other selected base station. The procedure adopted for the selection of the base stations is explained in the following sections. Assume that the central control unit has the following information

Base Station	Monitored Base Stations
0	1, 2, 3, 4,
1	0, 2, 3, 5,
2	0, 1, 3, 6,
3	1, 2, 4, 7,
4	0, 5, 6, 7,
5	4, 6, 8, 9,
6	3, 4, 5, 7,
7	5, 6, 8, 9,
8	4, 7, 9, 10
9	5, 8, 10, 11
10	6, 8, 9, 11
11	7, 8, 9, 10

For example to select the other base stations, when updating timing at base station #4, the central control unit sequentially checks base station numbers upwards (i.e. #5 #6 #7 ..... #11) and downwards (#3 #2 #1 #0) one by one, and determines if it is possible to turn off the transmission simultaneously.

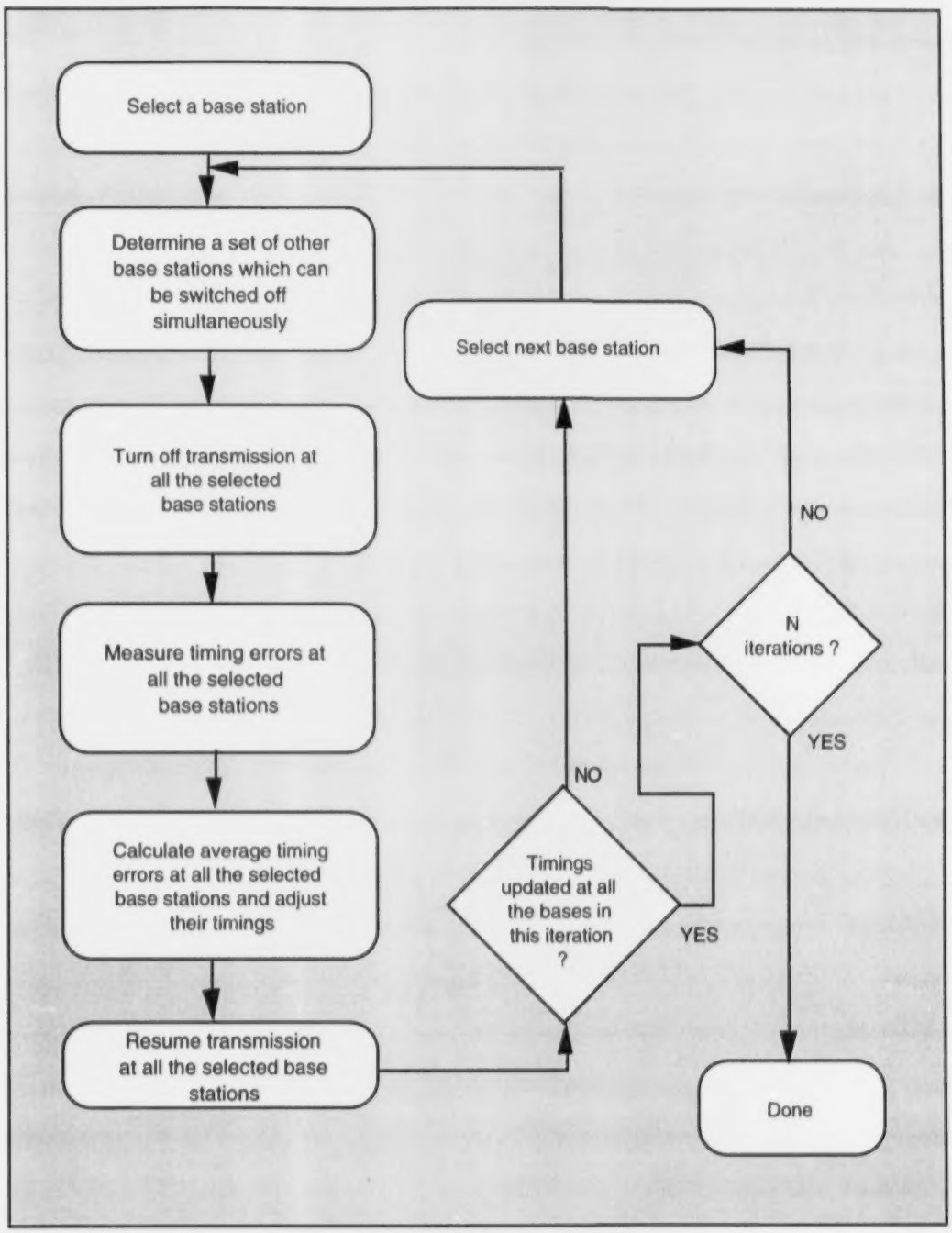
Select a base station
Determine a set of other base stations which can be switched off simultaneously
Turn off transmission at all the selected base stations
Measure timing errors at all the selected base stations
Calculate average timing errors at all the selected base stations and adjust their timings
Resume transmission at all the selected base stations
Timings updated at all the bases in this iteration ?
NO
YES
Select next base station
N iterations ?
NO
YES
Done

Figure 2.2 Flow Diagram for Simultaneous Updating at a Number of Base Stations

First, the central control unit checks if the base station is required for timing error measurement by any other base station which has already been selected for updating its timing. In this case while moving upwards, base station #5, #6, and #7 can not update their timings simultaneously because the signal from these base stations is required for timing updating at the base station #4.

Secondly, the control unit checks if the base station requires signals from any of base station which has already been selected (turned off). So, in this case, although the next base station #8 is not required for the timing update at the base station #4, but the base station #8 requires base station #4 for its timing update, so it can not be selected. Base station #9 can update its timing simultaneously because neither base station #4 requires base station #9 for its timing update nor the base station #9 requires base station #4 for its timing update. Similarly all other possible base stations are determined which can be turned off for synchronization simultaneously.

2.2.3 Hierarchical Over-the-Air Synchronization

This approach is a hybrid method based on over-the-air synchronization and the hierarchical scheme[10], in which the timings of the base stations higher in hierarchy are made to propagate through the system. In this method some base stations' timings are considered master timings. All master base stations are given an initial hierarchical value, H = 0. All other base stations are initialized to a higher H value, e.g. 4, if only 4 other base stations are considered in timing adjustment.

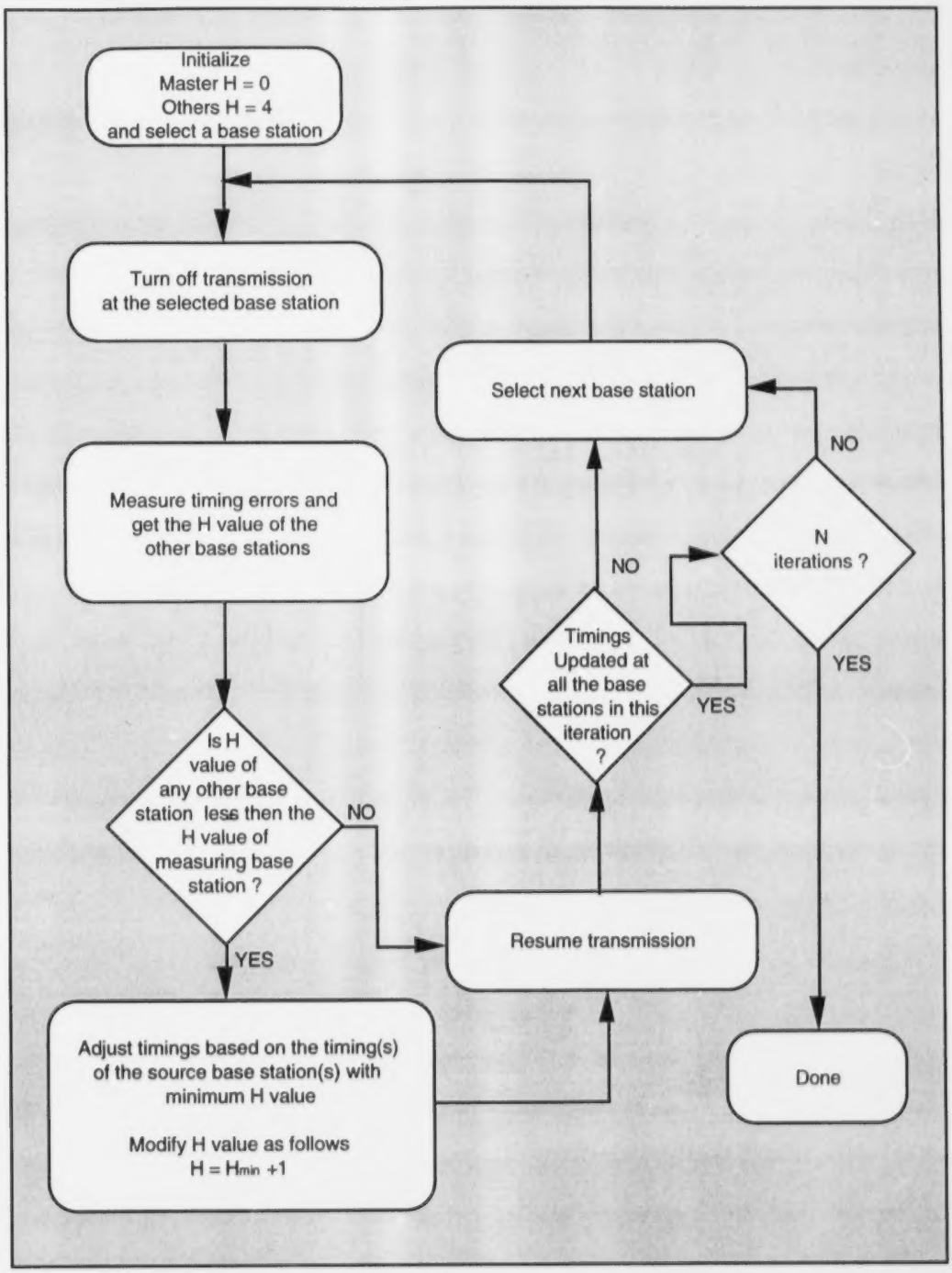

Figure 2.3 Flow Diagram for Hierarchical Method

The H value of the receiving base station (base station at which the timing is being adjusted) is compared to the H value of the source base stations (base stations from which a signal is being received). The timing is adjusted only if the H value of one or more source base station(s) is smaller than the H value of the receiving base station. The timing of the receiving base station is adjusted based on the timing(s) of the source base station(s) with the smallest H value. Similar weighting strategies as in the earlier sections can be applied.

If the timing is adjusted at the receiving base station, its H value is modified to $H_{min}+1$ as shown in the Figure 2.3. H_{min} is the H value of the source base station(s) from which the timing is being updated. All the master base stations should be initially exactly synchronized with each other. If even one of the master base stations is initially not synchronized then some of the base stations will not be synchronized after the process is complete.

All of the approaches which have been discussed in this chapter have been evaluated by simulations. The next chapter describes the details of the simulation models used for evaluating these synchronization techniques.

Chapter 3

Simulation Model

3.1 Introduction

Simulations play an important role in the design, analysis, and implementation of communication and signal processing systems. Today's communications systems are much more complex than those of several years ago and can no longer be designed and analyzed using only traditional mathematical analysis. Simulation is a convenient and cost effective method for verification of the functionality and evaluation of the performance of complex, high cost, and high risk systems. In this project computer simulations are used to evaluate the performance of techniques for synchronization of base stations in a digital cellular system. The simulation models were written using C in a UNIX environment.

3.2 System Model for the Simulations

In this project we have considered an indoor building environment and implemented the DECT (Digital European Cordless Telecommunication) standards. This chapter provides a brief description of the relevant DECT standards, the indoor building environment, the propagation channel, and the base station implementations used in the project.

3.2.1 DECT (Digital European Cordless Telecommunications)

DECT is a multi carrier, TDMA, TDD cordless telecommunication system. DECT can be used in a variety of environments but it is primarily intended for voice and data communications in business, telepoint and residential environments. It is designed to support integrated telecommunication applications such as business PABX, residential telephony with intercom facility, ISDN connection, video phone, and batch file transfers [11].

The DECT system operates at a channel bit rate of 1.152 Mb/s. The modulation scheme is GMSK (Gaussian Minimum Shift Keying) with a BT product of 0.5. The system has 10 carrier frequencies with a channel spacing of 1.728 MHz, occupying a band from 1.88 GHz to 1.9 GHz. Each RF channel can support up to 12 independent calls via time division duplexing (TDD). TDD is achieved by changing the direction of transmission after every 12 time slots (every 5 ms; see Figure 1.4). The frame rate is 100 Hz. Each data occupying a single time slot packet consists of 32 synchronization bits, 388 data bits, and 60 guard bits. The synchronization field consists of a 16 bit symbol synchronization preamble and a 16 bit frame synchronization word [5].

3.2.2 Indoor Building Environment

In this project a three dimensional indoor building environment is considered. As shown in Figure 3.1, the building has 3 floors and the distance between the floors is 3 meters. Each floor is 60 meters by 60 meters. Four base stations are placed on each floor. Adjacent base station spacing is 30 meters.

The base stations on each floor are aligned i.e. the base stations are located directly one over another.

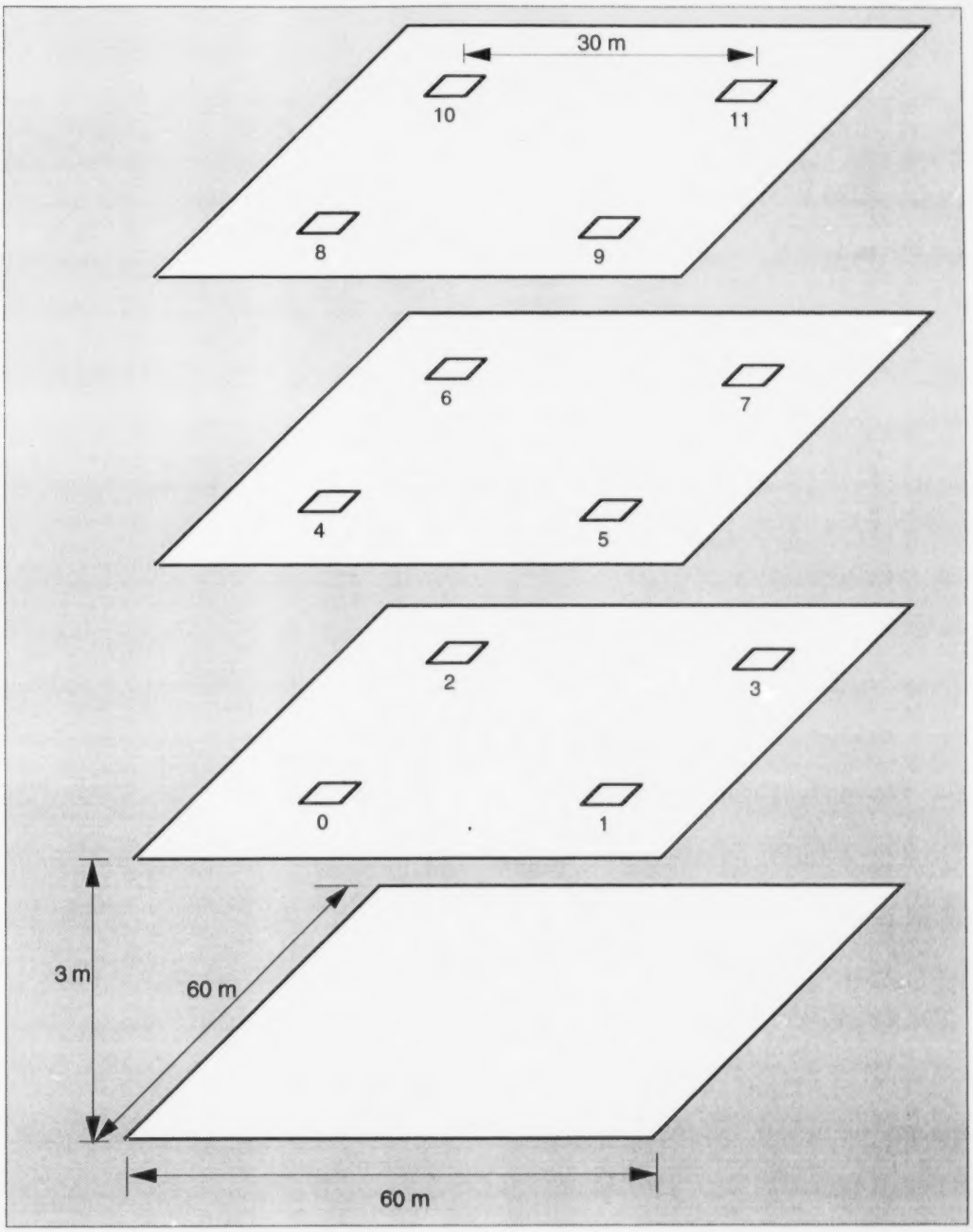

Figure 3.1 Indoor Building Environment

To evaluate the effect of the size of the system a bigger system is also considered. In this system there are 9 base stations on each floor. Adjacent base station spacing is 20m.

3.2.3 Propagation Channel

A typical indoor propagation channel is considered for the simulations. We have considered path loss, shadowing, Rayleigh fading, and propagation delays in the channel model.

3.2.3.1 Path Loss

Path loss describes the large-scale attenuation of the signal strength over distance. A number of models have been proposed in the literature for path loss simulation which are based on actual measurements in different indoor environments [12,13,14]. The parameters of these models vary significantly because they depend heavily on the environment. For this project we have selected a model which is based on the measurements taken in an environment which closely resembles the one described in Section 3.2.2 [15]. In this model the path loss is given by

$$L_m = 20 \cdot \log\left(\frac{4\pi d}{\lambda}\right) + L_l + kF(k) + pW(p) \qquad \text{...(3.1)}$$

where λ is the wavelength of the signal, d is the distance between the transmitter and receiver. In Equation 3.2 the first term is free space path loss, L_l is linear attenuation factor, F and W are floor and wall attenuation factors in dB, and k and p are the number of floors and the walls traversed by the direct ray. A

simplified model is used for the simulations. The path loss in the simulated model is given by

$$L_m = 20 \cdot \log\left(\frac{4\pi d}{\lambda}\right) + kF + pW \qquad \text{...(3.2)}$$

In the simulations the floor attenuation factor F has been set at 12 dB, the wall attenuation factor W at 2.2 dB, and p, number of walls between two base stations on a floor, was 5.

3.2.3.2 Shadowing

This long term fading effect inside the buildings is due to the radio shadows caused by stair wells, elevator shafts, furniture, and walls etc.. To account for shadowing a uniformly distributed random number between +10 dB and -10 dB is added to the path loss [16]. The shadowing factor is assumed to remain constant for the duration of the synchronization process.

3.2.3.3 Rayleigh Fading

The radio signal is also reflected and scattered by the walls, floors, ceilings and other objects inside the building. These multiple reflections result in many different paths between transmitter and receiver. This is known as multipath. One of the major effects of multipath is the possible destructive interference if the reflected wave(s) is out of phase with direct path signal or another strong signal from a different path. The amplitude of the received signal

in the multipath environment is Rayleigh distributed, and that is why this fading effect is also known as Rayleigh fading. The phase of the received signal is uniformly distributed between 0 and 2π [17]. In our simulation the Doppler frequency is set to 1 Hz (which corresponds to the velocity of less than 0.6 km/hr at 1.8 GHz). An example of Rayleigh fading is shown in Figure 3.2. Rayleigh fading is simulated by the offset oscillator method as shown in Figure 3.3 [18].

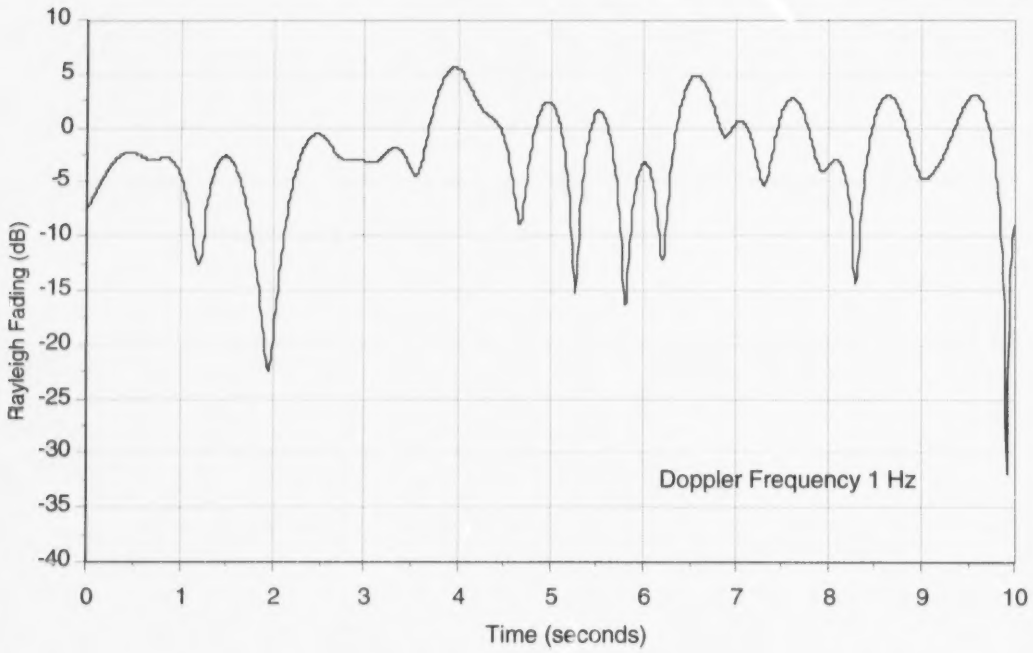

Figure 3.2 Rayleigh Fading

Although the base stations are stationary with respect to each other we have assumed a Doppler frequency of 1 Hz, in order to take into account the effect of the movement of people and other moving objects inside the building. In the simulation model, the propagation channel is implemented as shown in Figure 3.4.

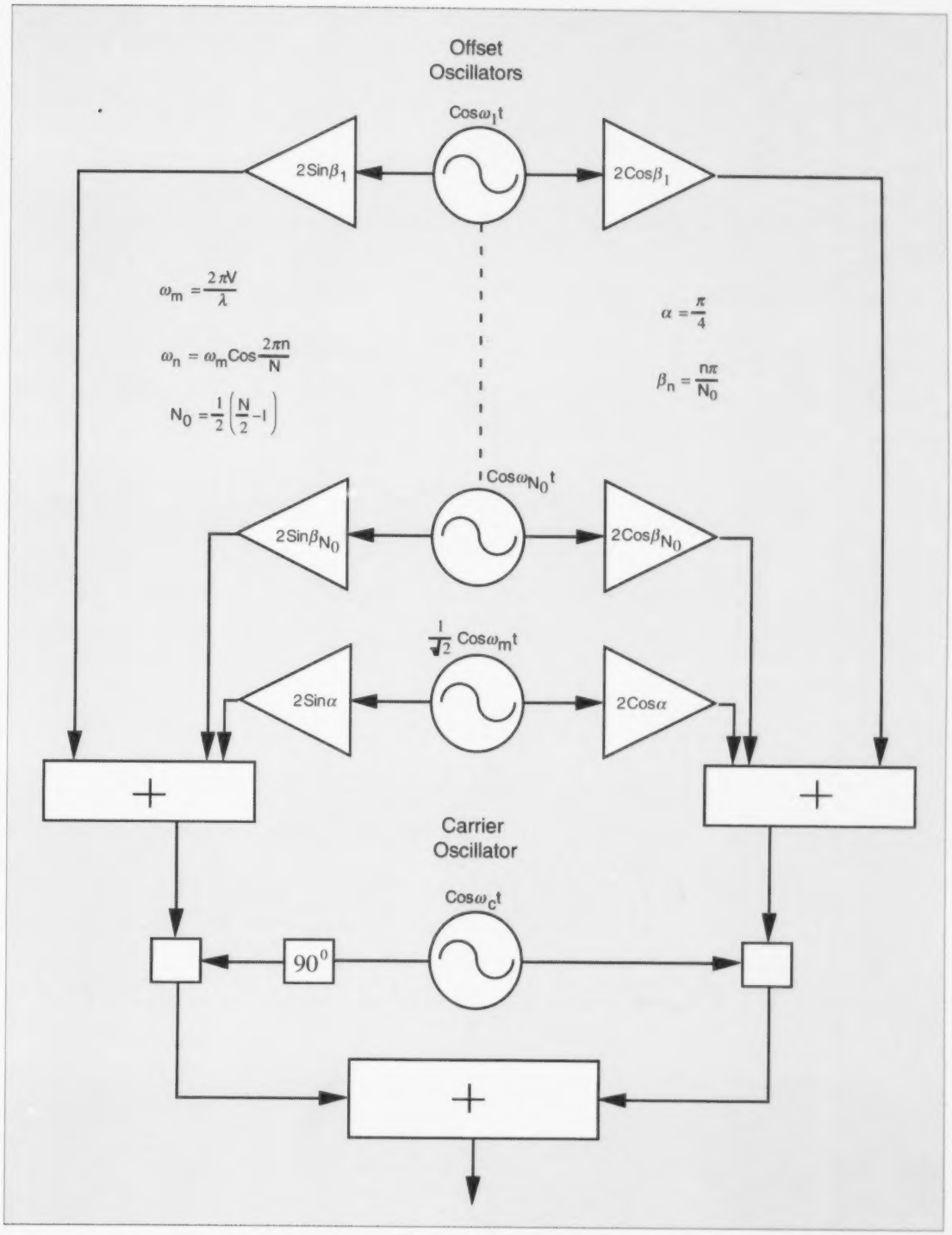

Figure 3.3 Offset Oscillator Rayleigh Fading Simulator

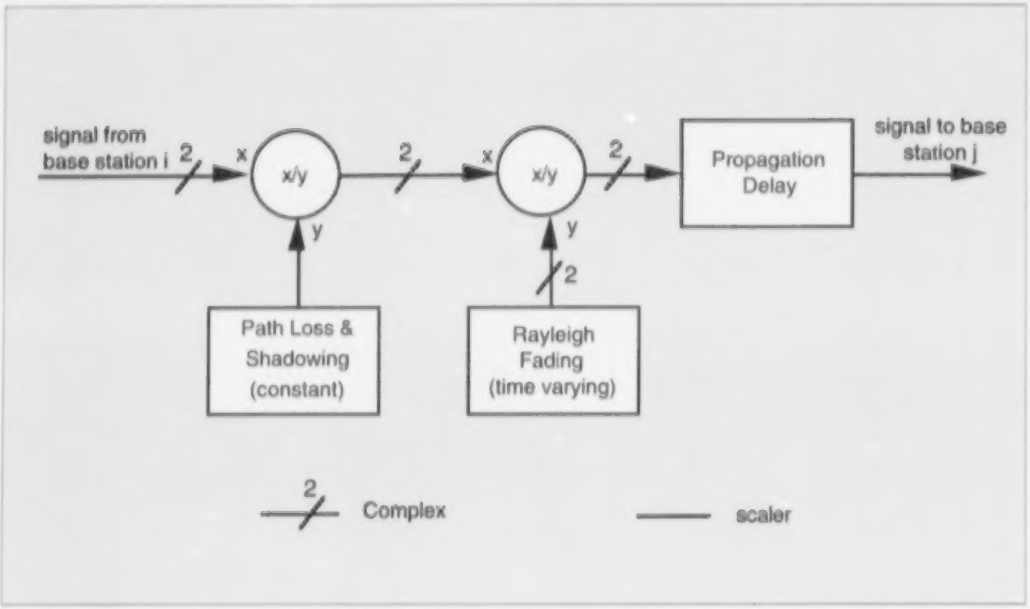

Figure 3.4 Simulation Model of the Propagation Channel

3.3 Base Station

The schematic block diagram of a base station is shown in Figure 3.5. In the simulation model we have implemented GMSK modulator, demodulator, and Frame timing detection module. Simulation reported here are based on idealized modem and channel model as a consequence these modules do not affect the results. However, this comprehensive simulation model could be used in the future to study the effect of measurement error, receiver sensitivity, noise and interference on the synchronization process. The base station is implemented in two parts;

1. Transmitter
2. Receiver

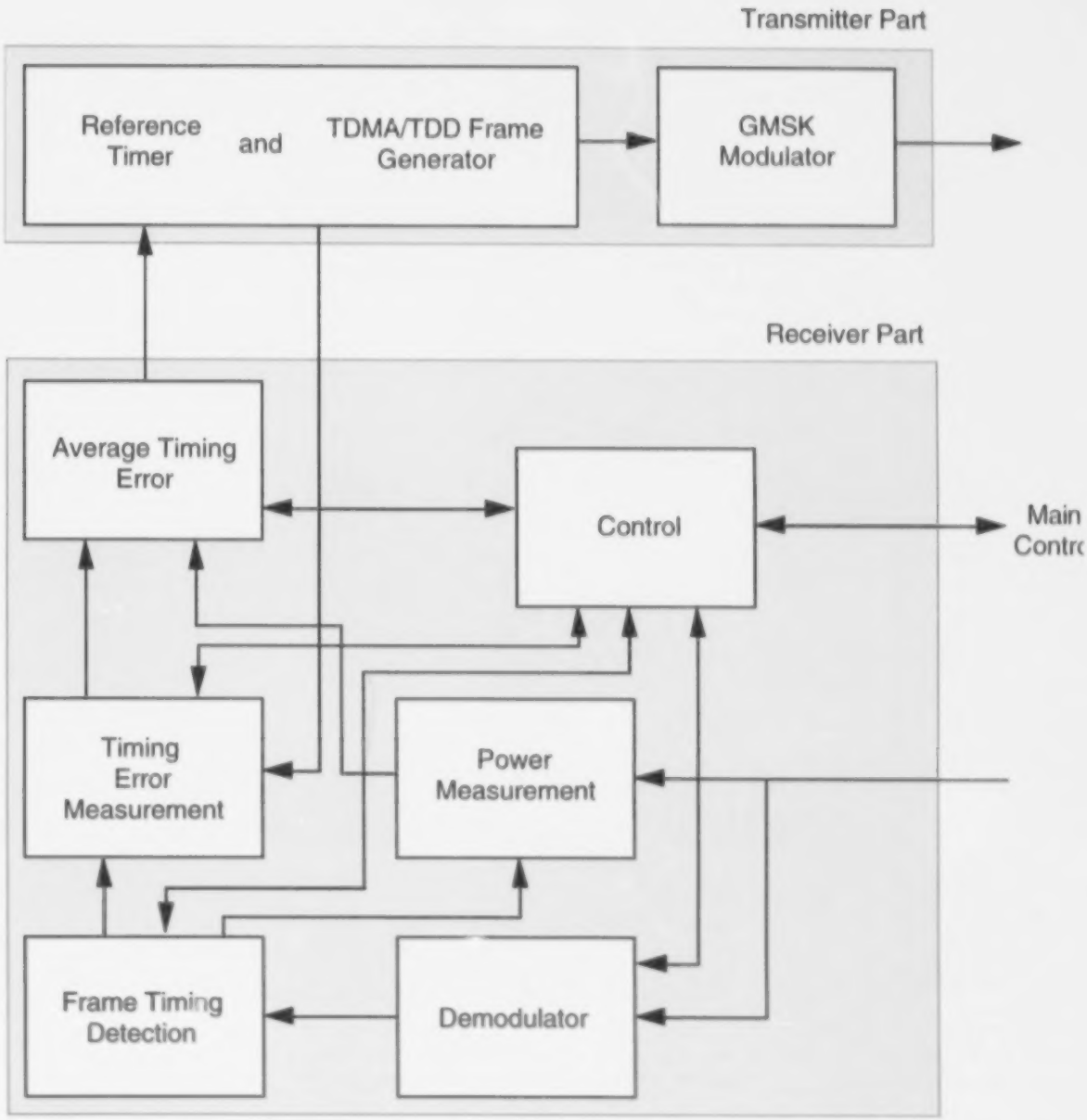

Figure 3.5 Schematic diagram of Base Station

3.3.1 Transmitter

The transmitter part contains the following two modules:

1. Reference Timer and TDMA/TDD Frame Generator
2. GMSK Modulator

3.3.1.1 Reference Timer and TDMA/TDD Frame Generator

The reference timer regulates the frame timing of the base station. The DECT frame has 11520 bits in every frame. Each bit is sampled eight times. So there are 92160 samples in each frame. In this project the reference timer keeps track of the number of samples in frames which have already been transmitted. It points to a sample number between 0 and 92159, where 0 denotes the beginning and 92159 denotes the end of the current frame as explained in Figure 3.6. At the beginning of the simulations the reference timers at all base stations are initialized to a uniformly distributed random number between 0 and 92159 i.e. between 0 and 10 ms.

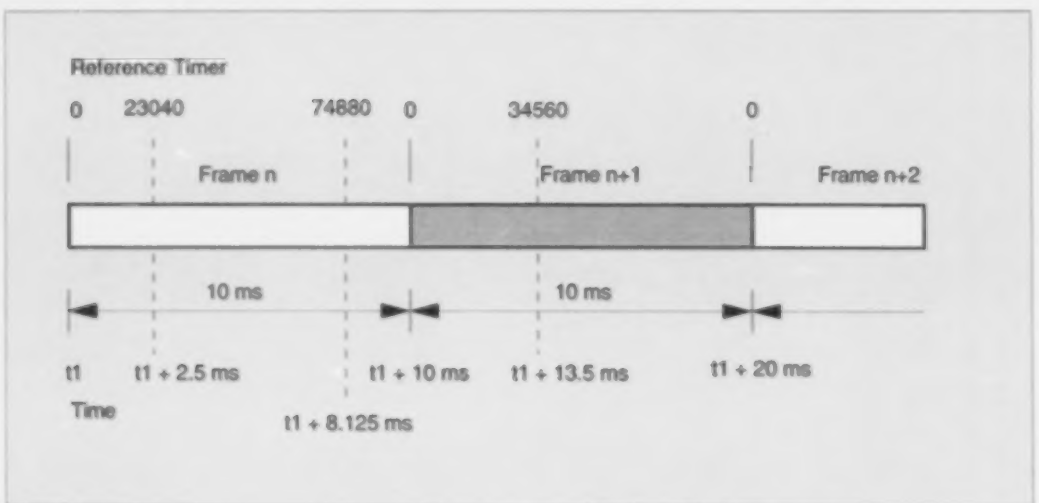

Figure 3.6 Reference Timer

The frame generator generates the data bit stream according to the frame defined in the DECT standards. The structure of the frame generated is shown in Figure 3.7. In every 10 ms the base station transmits for 5 ms. During this period it transmits data in 12 slots.

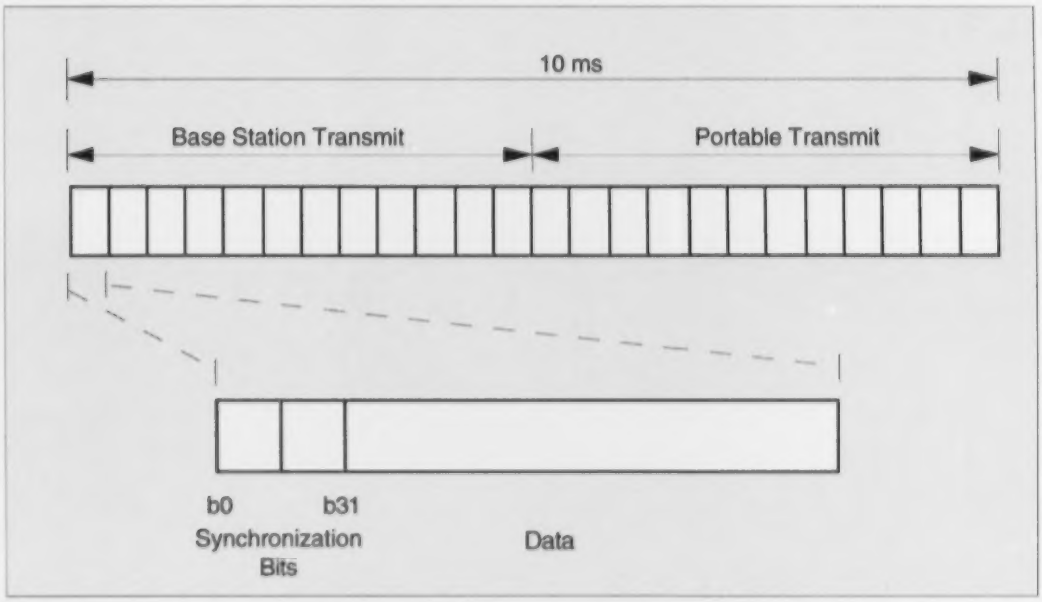

Figure 3.7 Frame Structure

The first 32 bits of every slot are known as synchronization bits. For base station transmission these bits are defined as shown in Figure 3.8. The frame generator module generates these synchronization bits at the beginning of every slot and for the rest of the slot random data is generated. These synchronization bits are used to detect the frame timings.

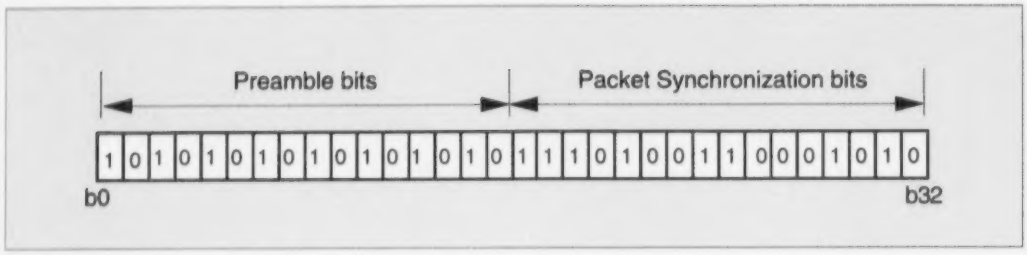

Figure 3.7 Synchronization bits

3.3.1.2 GMSK Modulator

The DECT standard has adopted Gaussian Minimum Shift Keying (GMSK), which is a modification of the Minimum Shift Keying (MSK). The schematic diagram of the GMSK modulator is shown in Figure 3.9.

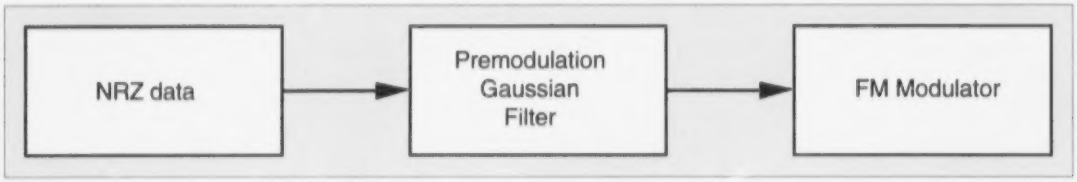

Figure 3.9 GMSK Modulator

The data source generates a stream of non-return-zero (NRZ) rectangular pulses given by

$$c(t) = \sum_{n=-\infty}^{\infty} a_n \Omega\left(\frac{t-nT}{T}\right) \qquad ...(3.3)$$

where a_n (± 1) represents the binary data, and $\Omega(t/T)$ is a unit rectangular pulse of duration T, centered at the origin. This NRZ signal is filtered through a low pass Gaussian filter to suppress out-of-band spurious power in the modulated signal. The premodulation Gaussian filter has $B_tT = 0.5$, where B_t is the 3 dB

cutoff frequency of the Gaussian filter, and T is the input data bit period. The transfer function of the premodulation Gaussian filter is given by [19]

$$H(f) = A\exp\left[-\left(\frac{f}{B_t}\right)^2 \frac{\ln 2}{2}\right] \qquad ...(3.4)$$

Where A is a scaling constant. The inverse Fourier transform function of this function gives the corresponding impulse response as

$$h(t) = A\sqrt{\frac{2\pi}{\ln 2}}B_t \cdot \exp\left(-\frac{2\pi^2 B_t^2 t^2}{\ln 2}\right) \qquad ...(3.5)$$

The convolution of the input data signal c(t) and the impulse response of the Gaussian filter h(t) gives input signal to the FM modulator, which is given by

$$b(t) = \sum_{n=-\infty}^{\infty} a_n g(t - nT) \qquad ...(3.6)$$

where g(t) is the Gaussian pulse given by

$$g(t) = \Omega\left(t/T\right) * h(t) \qquad ...(3.7)$$

The output of the Gaussian filter b(t) frequency modulates an RF carrier. The modulation index h ($h = 2Tf_d$) is 0.5, where f_d is the maximum frequency deviation. The output of the modulator can be expressed as

$$S(t) = \cos(2\pi f_c t + \Phi_s(t)) \qquad ...(3.8)$$

where

$$\Phi_s(t) = 2\pi f_d \int_{-\infty}^{t} \sum_{n=-\infty}^{\infty} a_n g(\upsilon - nT) d\upsilon \qquad ...(3.9)$$

where $\Phi_s(t)$ is the change in the phase of the RF carrier due to modulation. The phase change over one bit period -T/2 to T/2 is $\pi/2$ +ISI. This can be shown as follows:

$$\Phi_s\left(\frac{T}{2}\right)-\Phi_s\left(-\frac{T}{2}\right)=2\pi f_d\int_{-\infty}^{T/2}\sum_{n=-\infty}^{\infty}a_n g(\upsilon-nT)d\upsilon$$

$$-2\pi f_d\int_{-\infty}^{-T/2}\sum_{n=-\infty}^{\infty}a_n g(\upsilon-nT)d\upsilon \qquad ...(3.10)$$

$$=2\pi f_d\int_{-T/2}^{T/2}\sum_{n=-\infty}^{\infty}a_n g(\upsilon-nT)d\upsilon \qquad ...(3.11)$$

$$=\sum_{n=-\infty}^{\infty}a_n p_n \qquad ...(3.12)$$

where

$$p_n=2\pi f_d\int_{-T/2}^{T/2}g(\upsilon-nT)d\upsilon \qquad ...(3.13)$$

$$=2\pi f_d\int_{-T/2-nT}^{T/2-nT}g(\upsilon)d\upsilon \qquad ...(3.14)$$

from Equations 3.12 and 3.14

$$a_0p_0=\frac{\pi}{2} \qquad \text{for } n=0 \qquad ...(3.15)$$

where a_0p_0 represents the phase change over one bit period and

$$\sum_{\substack{n=-\infty\\ n\neq 0}}^{\infty}a_n p_n$$

represents the intersymbol interference (ISI)

3.3.2 Receiver

The receiver part contains the following five modules:

1. Demodulator
2. Power Measurement module
3. Frame Timing Detection
4. Timing Error Measurement
5. Average Timing Error

3.3.2.1 Demodulator

One bit differential detector is used for the demodulation of the received signal. The schematic diagram of one bit differential demodulator is as shown in the Figure 3.10 [20].

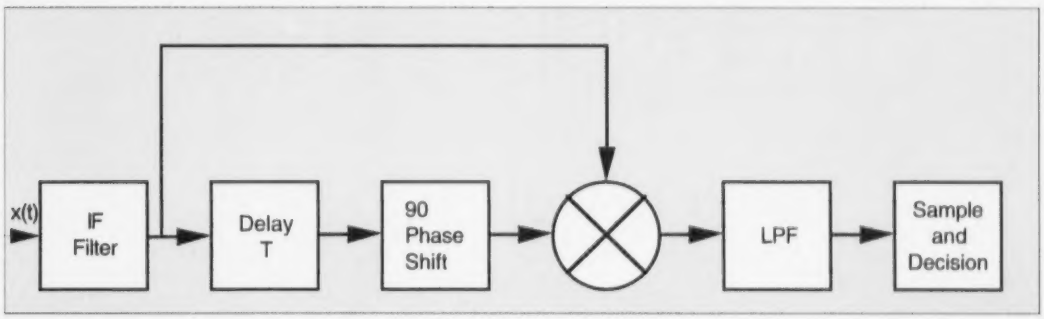

Figure 3.10 Demodulator

The signal received at the input of the predetection filter is given by

$$x(t) = \sqrt{2S} \cdot \cos\left(2\pi f_c + \Phi_s(t)\right) \qquad ...(3.16)$$

where S is the signal power, f_c is the carrier frequency, and $\Phi(t)$ is the transmitted phase deviation after frequency modulation. The received signal is

first filtered by a Gaussian IF filter which has the equivalent lowpass transfer function

$$H_r(f) = \exp\left(-\frac{2\ln 2 f^2}{B_r^2}\right) \qquad ...(3.17)$$

This filter band limits x(t) which results in a time varying envelope $\sqrt{2S}a(t)$.

$$x_{IF}(t) = \sqrt{2S}\cdot a(t)\cos(2\pi f_c t + \Phi_s(t)) \qquad ...(3.18)$$

or
$$x_{IF} = R(t)\cdot\cos(2\pi f_c t + \Phi_S(t)) \qquad ...(3.19)$$

where
$$R(t) = \sqrt{2S}\cdot a(t) \qquad ...(3.20)$$

R(t) is the envelope of the signal. $x_{IF}(t)$ is multiplied by the delayed and phase shifted version of itself, that is delayed by a symbol time T and phase shifted by 90°.

$$y(t) = \left[R(t)\cdot\cos(2\pi f_c t + \Phi_S(t))\right] \cdot\left[R(t-T)\cdot\cos(2\pi f_c(t-T) + \pi/2 + \Phi_S(t-T))\right] \qquad ...(3.21)$$

$$y(t) = -R(t)\cdot R(t-T)\cdot\cos(2\pi f_c t + \Phi_S(t))\cdot\sin(2\pi f_c(t-T) + \Phi_S(t-T)) \qquad ...(3.22)$$

$$y(t) = -\frac{R(t)\cdot R(t-T)}{2}\left[\sin(2\pi(2f_c)t - 2\pi f_c T + \Phi_S(t) + \Phi_S(t-T))\right] + \frac{R(t)R(t-T)}{2}\left[\sin(2\pi f_c T + \Phi_S(t) - \Phi_S(t-T))\right] \qquad ...(3.23)$$

ignoring the higher frequency ($2f_c$) term in the expression we get

$$y(t) = \frac{R(t) \cdot R(t-T)}{2} \sin(2\pi f_c T + \Delta\Phi(T)) \quad ...(3.24)$$

where

$$\Delta\Phi(T) = \Phi(t) - \Phi(t-T) \quad ...(3.25)$$

On the basis of equations $\Delta\Phi(T)$ represents the change of phase over one symbol time. We assume that the carrier frequency is chosen such that $f_c T = k$. Where k is an integer.

In that case the Equation 3.24 reduces to

$$y(t) = \frac{R(t) \cdot R(t-T)}{2} \sin(\Delta\Phi(T)) \quad ...(3.26)$$

On the basis of equations 3.15 , if $\sin(\Delta\Phi(T)) > 0$ "1" was sent otherwise a "0" was sent. Since the envelope R(t) is always positive then the equivalent decision rule is

"1" was sent if $y(t) > 0$

"0" was sent if $y(t) < 0$

3.3.2.2 Frame Timing Detection

This module detects the frame timing of the received signal. It searches for the synchronization bits pattern of the first time slot of a frame in the received signal bit stream. A simple procedure described below is adopted for detecting frame timing.

This module monitors the bit stream received from the demodulator to detect the timing of the received signal. In the DECT system the base station transmits for 5 ms in every 10 ms. When a base station starts monitoring the signal from another base station, the monitored base station may or may not be transmitting at that time. If the other base station is not transmitting at that particular moment, this module keeps waiting for the signal and as soon as the signal is received, the received data bits are matched with the synchronization bit pattern to confirm the timings. But if the signal is detected as soon as monitoring process begins, the received signal is ignored for the next 5 ms to avoid detection the synchronization bits of other than the first slot of the frame.

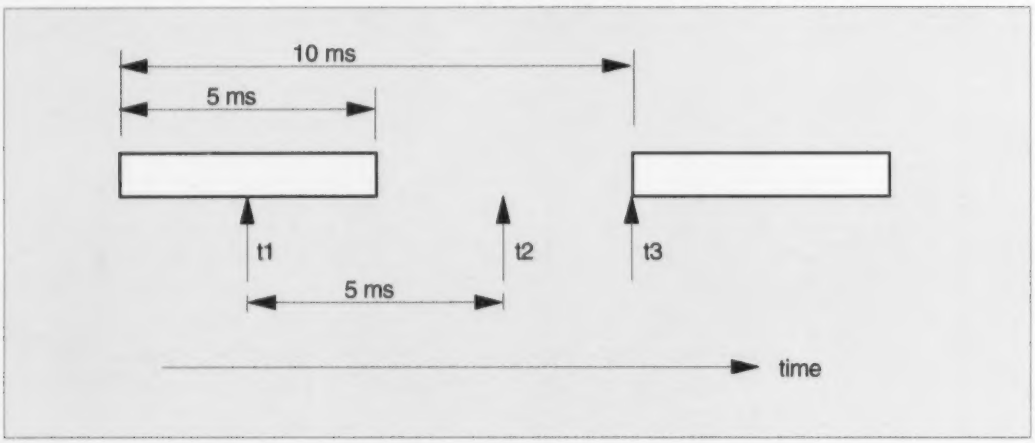

Figure 3.11 Frame Timing Detection

For example as shown in Figure 3.11 the base station starts monitoring the signal at time t1. To correctly determine the timing it ignores the received signal for next 5 ms i.e. until time t2 and at time t2 it again starts monitoring the received signal and as soon as it is found (at time t3) it matches the received data with the synchronization bit pattern to confirm the frame timing.

3.3.2.3 Power Measurement

The power measurement module measures the received signal strength. As soon as the frame timing detection module confirms the frame timing it instructs the power measurement module to start measuring power. This module measures the average of the received signal power until the end of the first slot. The propagation channel is almost stationary in time so the average of the signal strength over one time slot would provide a good measure of the received signal power.

3.3.2.4 Timing Error Measurement

To measure the timing error, the received signal data bits are compared with the synchronization bit pattern. Then the timing of the received signal is compared with the timing of the measuring base station to determine the timing error. This is explained in more detail in the next chapter. The actual timing error is obtained by subtracting the time taken by the signal in the modulation and demodulation process from the measured timing error. In this model the modulation and demodulation processes take 13 sampling periods.

3.2.2.5 Average Timing Error Calculation

This module calculates the average timing error. Every time the timing error and the power level is measured it is stored in the average timing module. When the measurements are complete, the average timing error is calculated

by one of the formulas given in the previous chapter, and the timing of the reference timer is modified accordingly.

Chapter 4

Results

4.1 Introduction

This chapter first explains the procedure for timing error measurement and the criteria used for evaluation of the results. Then the results are presented and discussed. The objective is to evaluate the performance of the synchronization algorithms. To establish the robustness of over-the-air synchronization the effects of synchronization order, the random updating of timings, presence of partitions, and the addition of a new base station to the system are evaluated. The results are presented for the sequential synchronization, simultaneous timing updating, and the hierarchical method.

4.2 Timing Error Measurement

The timing error measurement procedure consists of two processes:

1) Search and Confirmation of Frame Timing
2) Error Calculation.

In the search and confirmation mode the algorithm sequentially searches for the synchronization bit pattern in the received data bit stream until the match is found as explained in section 3.3.2.2. Timing error between two base stations is equal to the difference in the timings given by their respective reference timers. For example, as shown in Figure 4.1, the synchronization bits

of the source base station are matched at time t1 and at this time the receiving base station timing is x. To perform the search and confirmation it took y sample periods. So the reference timer of the base station from which the signal is received is y at time t1. The timing error between the two base stations is the difference of timings given by their respective reference timers i.e. (x - y) sample periods.

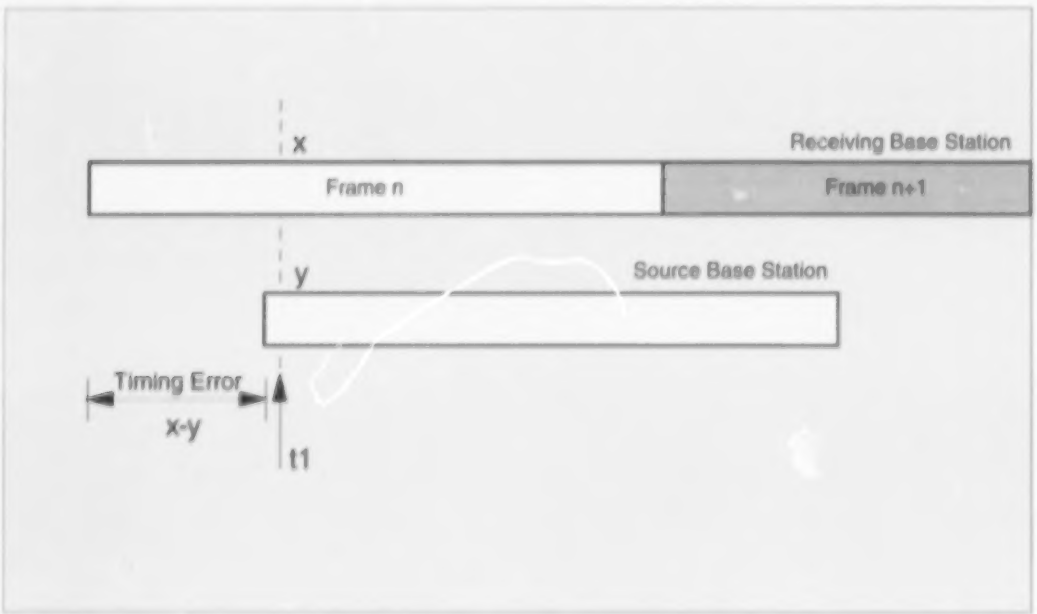

Figure 4.1 Time Error Measurement

The error should be measured between the frames which are closest to each other. If the error between the current frames of the receiving and the source base stations is more than half frame length, the error is measured with respect to the next frame of the receiving base station. As shown in Figure 4.2, the timings of the receiving base station and source base station at time t1 are x and y respectively. The timing error between the current frames is (x-y) sampling periods which represents more than a half-frame length. The

beginning of the frame of source base station is much closer to the beginning of the next frame than the current frame of the receiving base station. So the error is measured with respect to the next frame of the receiving base station. If each frame has f samples, the timing error is (x-y-f).

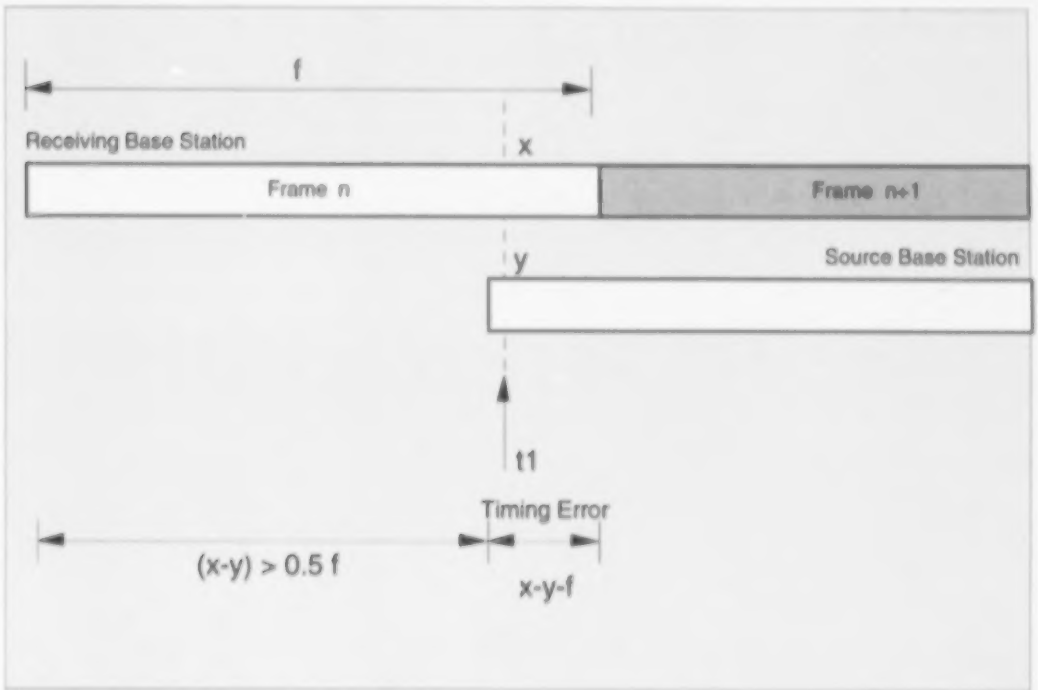

Figure 4.2 Timing Error Measurements

4.3 Criteria for the Evaluation of Results

The performance of the different synchronization algorithms was evaluated on the basis of the standard deviation of the timings of all the base stations in the system. The standard deviation of the timings is calculated after every iteration using the following formula

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(t_i - \bar{t}\right)^2} \qquad ...(4.1)$$

where N is total number of base stations in the system, t_i is the timing of the base i, and $\bar{t}$ is the mean of the timings which is given by

$$\bar{t} = \frac{1}{N}\sum_{i=1}^{N} t_i \qquad ...(4.2)$$

4.4 Results

The results are evaluated on the basis of the time taken by the system to reach the time synchronous state. The DECT standard requires base stations to be synchronized within 4 μs. The timings of the base stations are assumed to be uniformly distributed hence the standard deviation of their timings should be less than 1.154 μs $\left(4/\sqrt{12}\right)$ or 1.33 bit periods. The system is taken to be synchronized if the standard deviation of the timings is less than 1.33 bits.

The initial conditions refer to the initial timings of the base stations and the shadowing factors. In the beginning of the simulation the base stations are assigned randomly generated initial timings, which are uniformly distributed between 0 and 10 ms. The shadowing factors between the base stations are also generated randomly, they are uniformly distributed between +10 dB and -10 dB. Thus the different initial conditions refer to different sets of initial timings and shadowing factors.

To evaluate the performance the standard deviation of timings of the base stations in the system is plotted as a function of time. The total time taken

for each iteration is sum of the times taken to update timings at individual base stations. The total time taken to update timing at a base station is the sum of all times taken to measure the timing errors with respect to the other base stations in the system. In the procedure we have adopted for measurement of timing error the time taken to measure timing error would depend on the relative timings of the two base stations as explained in Section 3.3.2.2.

4.4.1 Effect of Using Power as the Weighting Factor

In sections 2.2 two weighting strategies are explained for the calculation of the average timing error. In one approach the timing errors are averaged with power as a weighting factor and in the other approach no weighting is applied.

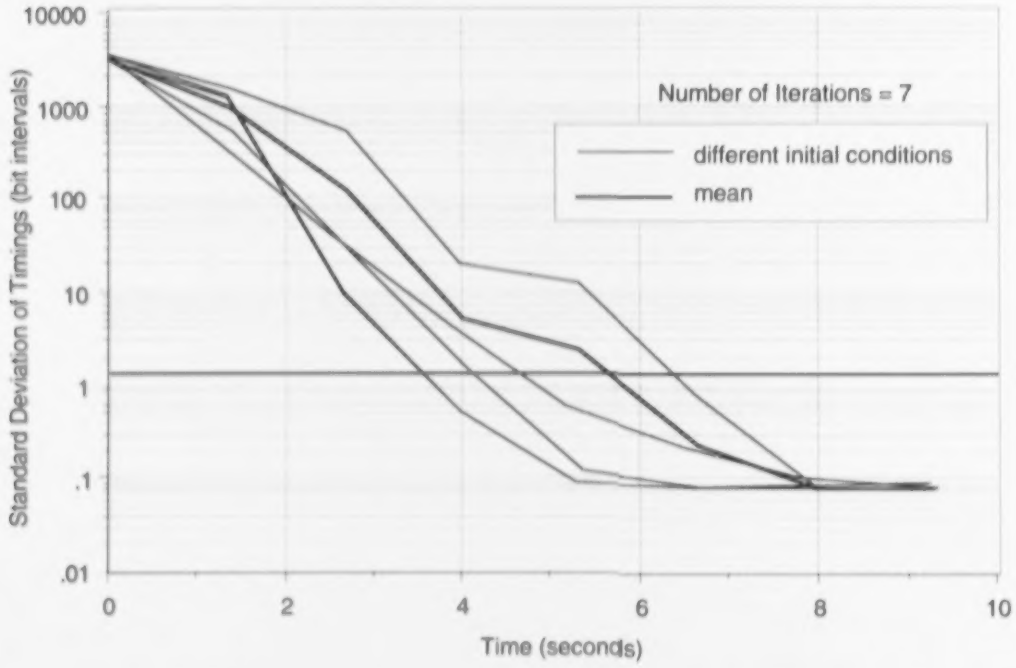

Figure 4.3 Timing Errors Averaged with Power as Weighting Factor

The results obtained for these weighting strategies are shown in Figure 4.3 and Figure 4.4. In these simulations the timings of the base stations are updated sequentially and the order of updating is 0, 1, 2, ... 10, 11, where 0,1,2 ..... 11 are the identification numbers given to the base stations as shown in Figure 3.1.

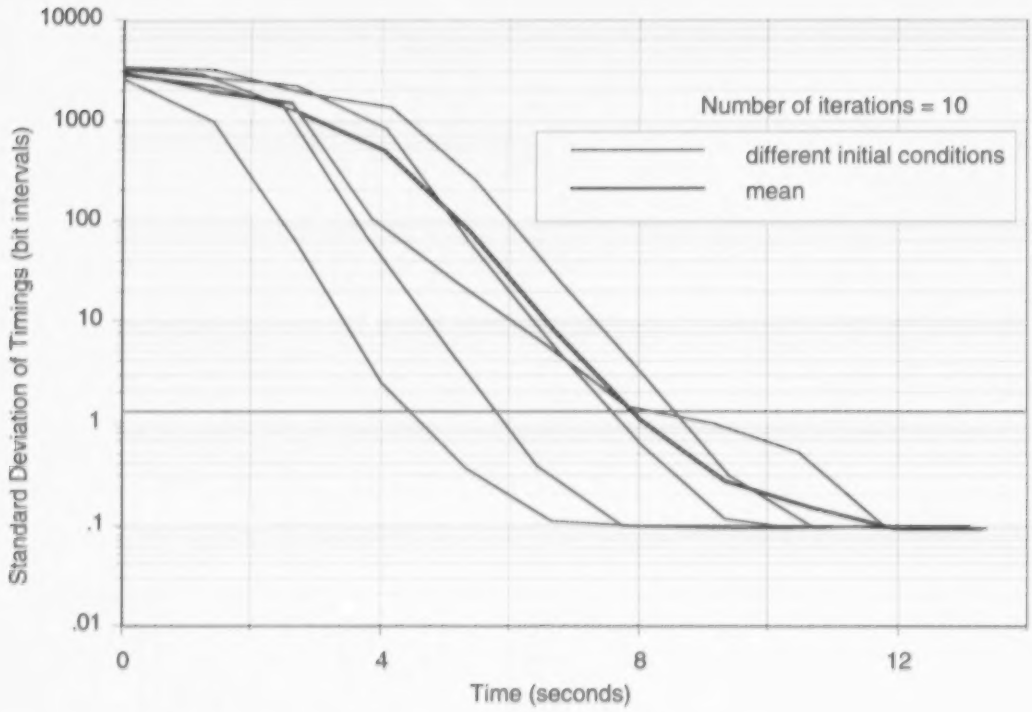

Figure 4.4 Timing Errors Averaged without Weighting

To determine the robustness for both weighting strategies the results are obtained for a number of different sets of initial conditions.

In the algorithm which uses power as the weighting factor, the timing errors with respect to the closer base stations are weighted heavily as compared to the distant base stations. This approach synchronizes more

quickly than the other approach. If the errors are weighted with power, it takes between 3.5 seconds to 6.5 seconds to synchronize and in the other case it takes between 4.5 to 8.5 seconds. The variation in the time taken to synchronize, for different initial conditions, is less when the error are weighted with power. Figure 4.5 shows the relative timings of the base stations in one of the simulation. The timings of the different base stations with respect to the base station #5 are plotted.

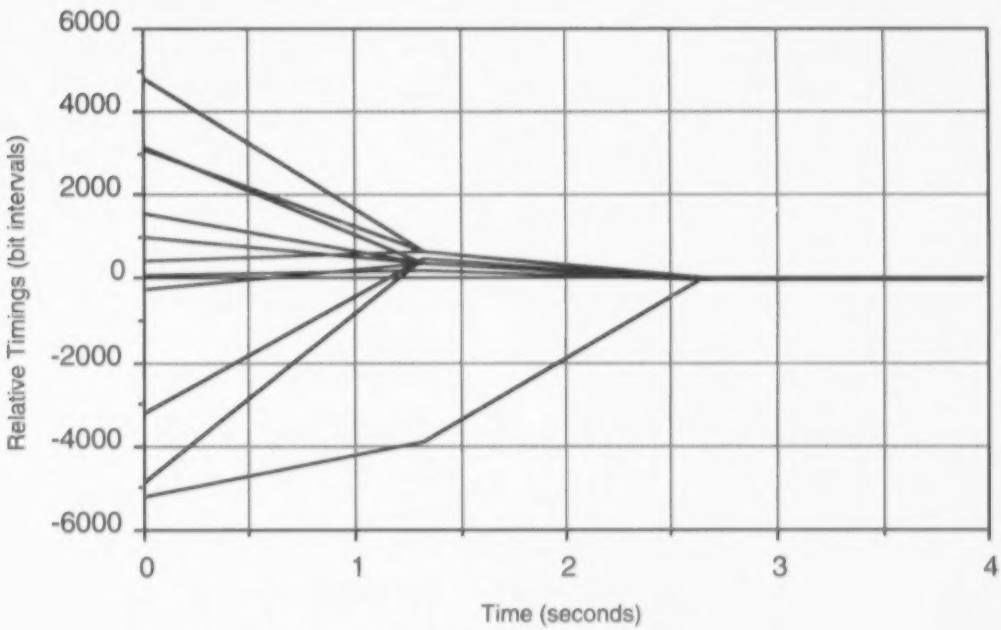

Figure 4.5 Relative Timings of the Base Stations

4.4.2 Effect of the Order of Updating the Timings

One of the factors which could affect the synchronization process is the order in which the base stations update their timings. To evaluate the effect of the order of updating the timings, the simulations were run for the same initial conditions (i.e. the same initial timings of the different base stations and the

same shadowing factors) with different sequential orders in which the timing of the base stations are updated.

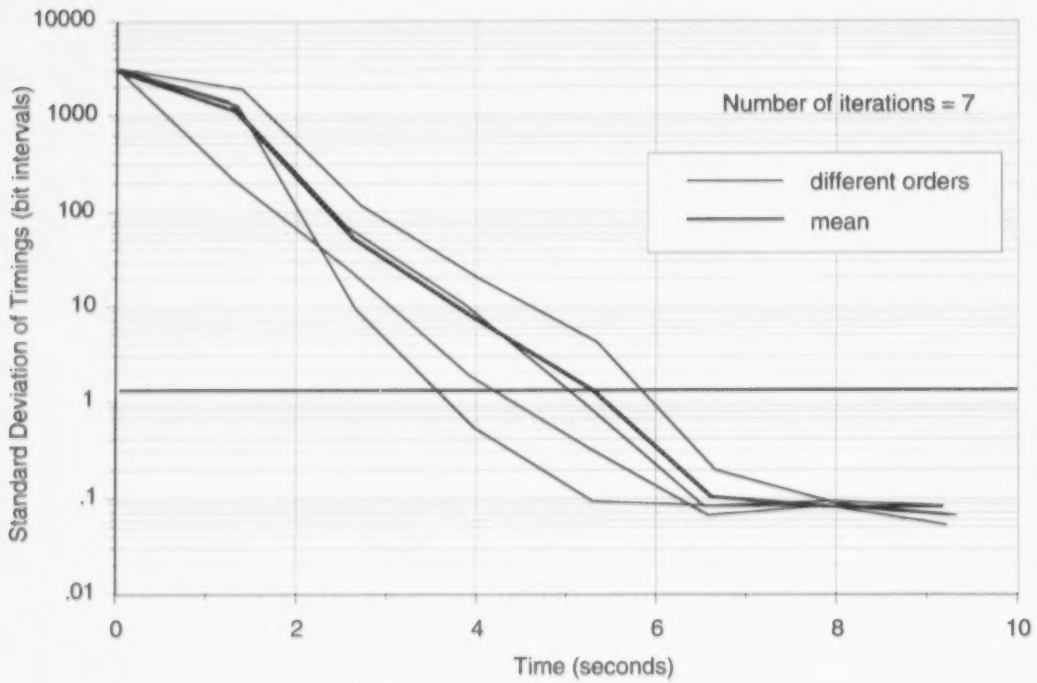

Figure 4.6 Effect of Order of Timing Updating

The orders of updating the timings assumed in the different simulations are as shown below.

	Order of updating the timings
1	0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11
2	5, 1, 9, 11, 8, 0, 6, 7, 4, 2, 10, 3
3	11, 10, 9, 8, 7, 6, 5, 4, 3, 2, 1, 0
4	7, 3, 8, 1, 9, 4, 6, 0, 10, 5, 11, 2

The results obtained for the different orders are shown in Figure 4.6. In all the cases power weighting strategy is used. The order of updating the timings does affect the synchronization process.

4.4.3 Effect of Random Updating of Timings

In sequential updating of timings the base stations in a system update their timings in a fixed sequence (order) in every iteration. The results of sequential updating of timings were presented in the previous section. Alternatively, the base stations could update their timings in a random order i.e. in every iteration all the base stations update their timings once but, the order of updating is different in every iteration.

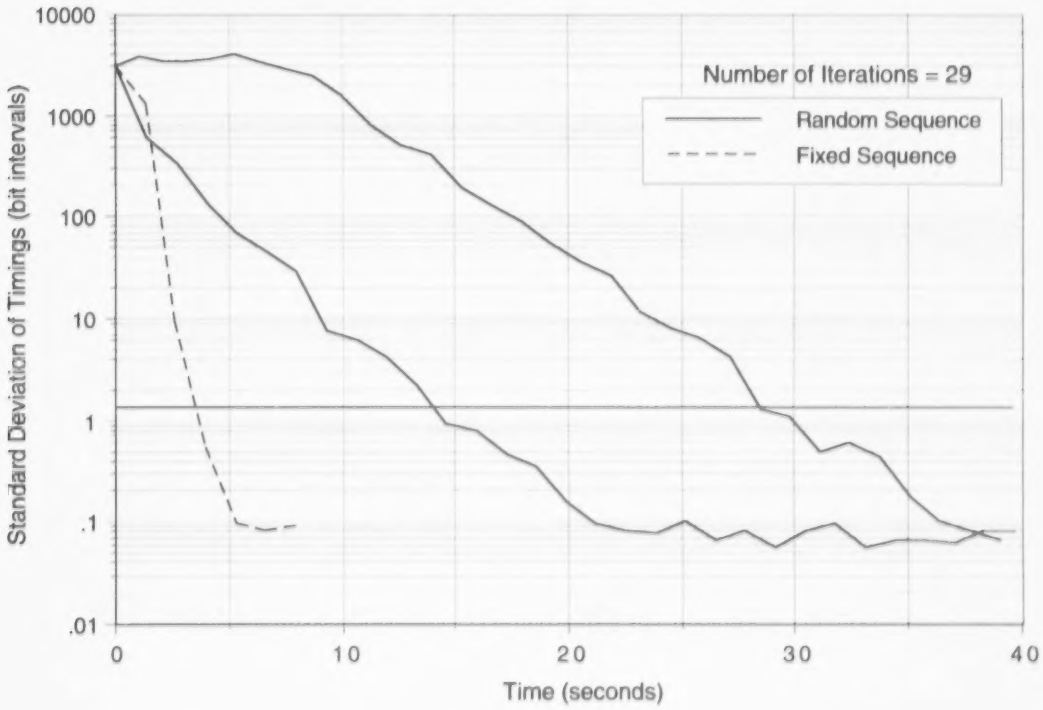

Figure 4.7 Effect of Random/order Timing Updating

The convergence time with random updating increases substantially relative to the fixed order updating in every iteration.

As shown in figure 4.7, for the same initial condition if the timings are randomly updated it takes much longer (15 and 27 seconds for two simulation runs) to reach the synchronous state, as compared to about 4.5 seconds for of sequential updating. In fixed order updating each base station updates its timing after every other base station has updated their timing once. In random updating every base station also, update its timings once in every iteration, however, the order of updating in successive iterations is different. So, unlike fixed order updating, the timings of some of the base stations are updated without every other base station being updated, this reduces the rate of convergence. On average only three quarters of monitored base stations have updated their timings between successive updates of a selected base station.

In the synchronization algorithms which have been simulated, the central controller determines measurement intervals for the different base stations (i.e. the time intervals during which different base stations should update their timings is decided by the main controller). This synchronization procedure requires the co-ordination of a the central controller. The synchronization procedure can be made more autonomous if the base stations select their own measurement intervals. Every base station would select its own measurement interval and pass the information to the central controller. So, in every iteration the order of updating will be different depending on when different base stations decide to update their timings. Therefore, the order of updating would change in every iteration, which is similar to what has been implemented in the random updating. Hence, the random updating of timings can be interpreted as an autonomous procedure requiring minimal intervention by a central controller.

4.5.4 Effect of Floor Partitions

A partition on a floor can heavily attenuate the signal received at a base station from the base stations on the other side of the partition. This could affect the synchronization process. To study this issue, in one of the simulations a partition is assumed on the second floor which separates the base stations #4 and #6 from base stations #5 and #7, as shown in Figure 4.8 and in another simulations a partition is assumed on the second floor which separates the base stations #4 and #5 from base stations #6 and #7. A 12 dB signal power attenuation is assumed due to the partition. As shown in Figure 4.9, the result for the case, when there is a partition, is very close to the case when there is no partition. This is because of the path losses and shadowing factors. The distance between two closest base stations on the same floor is 30m and the distance between the two closest base stations on different floors is just 3m. So, the path loss for the signal from a closest base station on a different floor is 20 dB less then the path loss for the signal from the closest base station on the same floor. Signal attenuation due to floor (12 dB) is comparable to the attenuation due to walls on a floor (11 dB) Therefore, the timing of a base station is more affected by the timings of the base station directly above and/or below than the other base stations on the same floor. Hence, there was no appreciable effect on the synchronization process due to the partition. The simulations were run for similar partitions on different floors and there was not much effect due to the partitions.

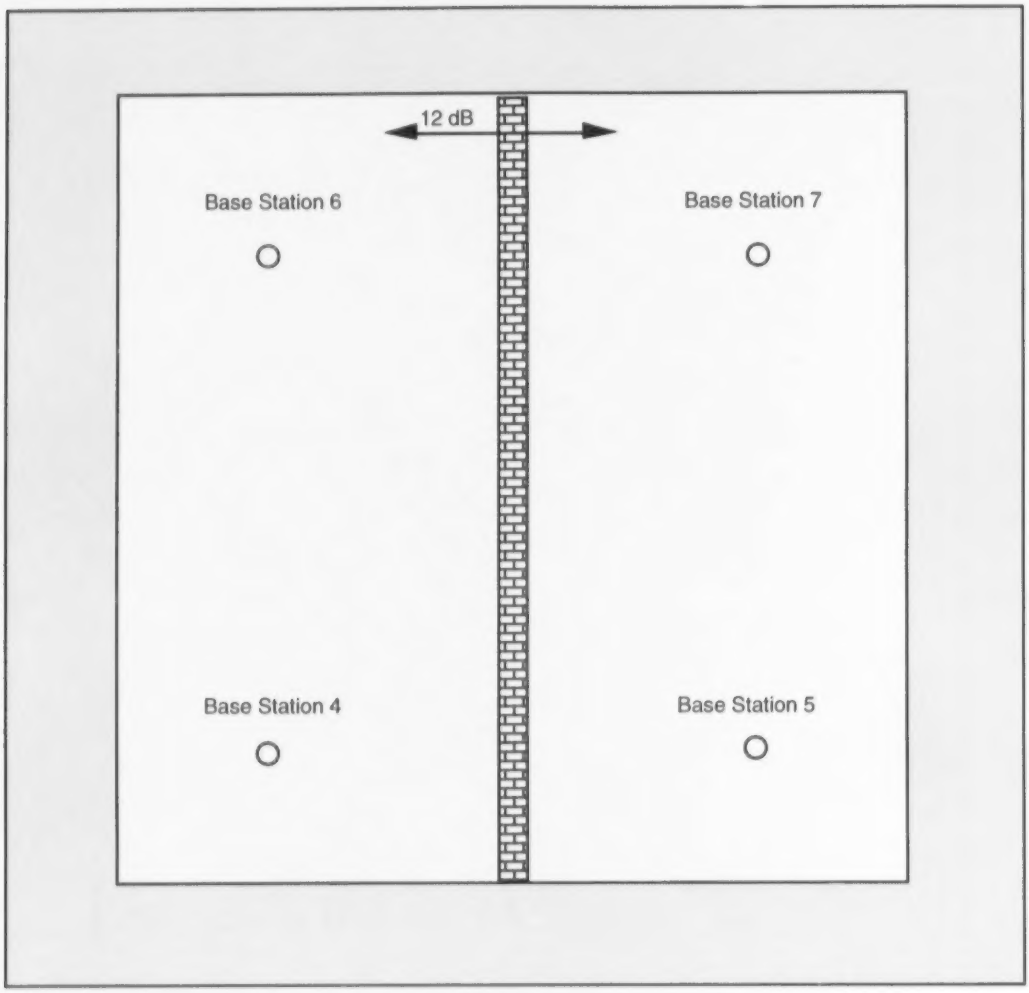

Figure 4.8 Partition on Second Floor

The shadowing factors, which are taken randomly distributed between -10 and +10dB, make the environment such that it could be assumed that there are randomly distributed obstructions inside the building. We have seen in the section 4.5.1 that the system synchronizes for the different shadowing conditions, this shows that the synchronization scheme is robust against partitions and other obstructions inside the building. There would be no effect on the performance of the algorithm in which the errors are not weighted.

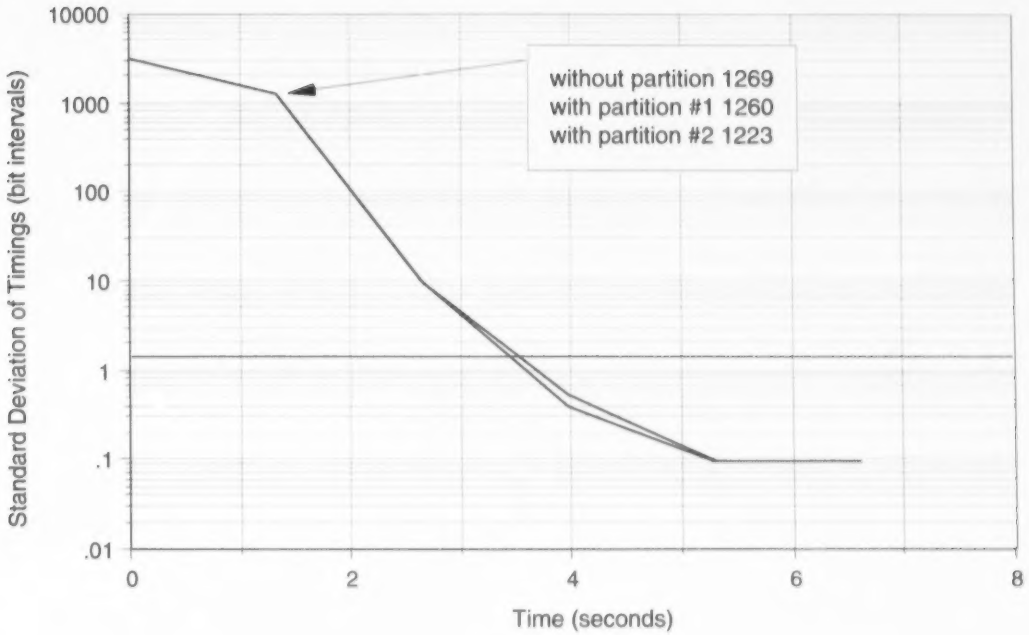

Figure 4.9 Effect of Partition

4.5.5 Effect of the Size of the System

To study the effect of the number of base stations in the system, on the time taken to synchronize, a larger system is studied. In this system every floor has nine base stations as shown in Figure 4.10. The distance between the adjacent base stations is 20 meters.

The results are shown in Figure 4.11. Every base station monitors the signal from 10 neighboring base stations in the system. The timings are updated in a fixed order and power weighting is used to calculate the average timing error. The convergence time increases as the number of base stations in the system increases. In case of 27 base stations it takes between 22 and 24 seconds to reach the time synchronous state as compared to about 5 seconds

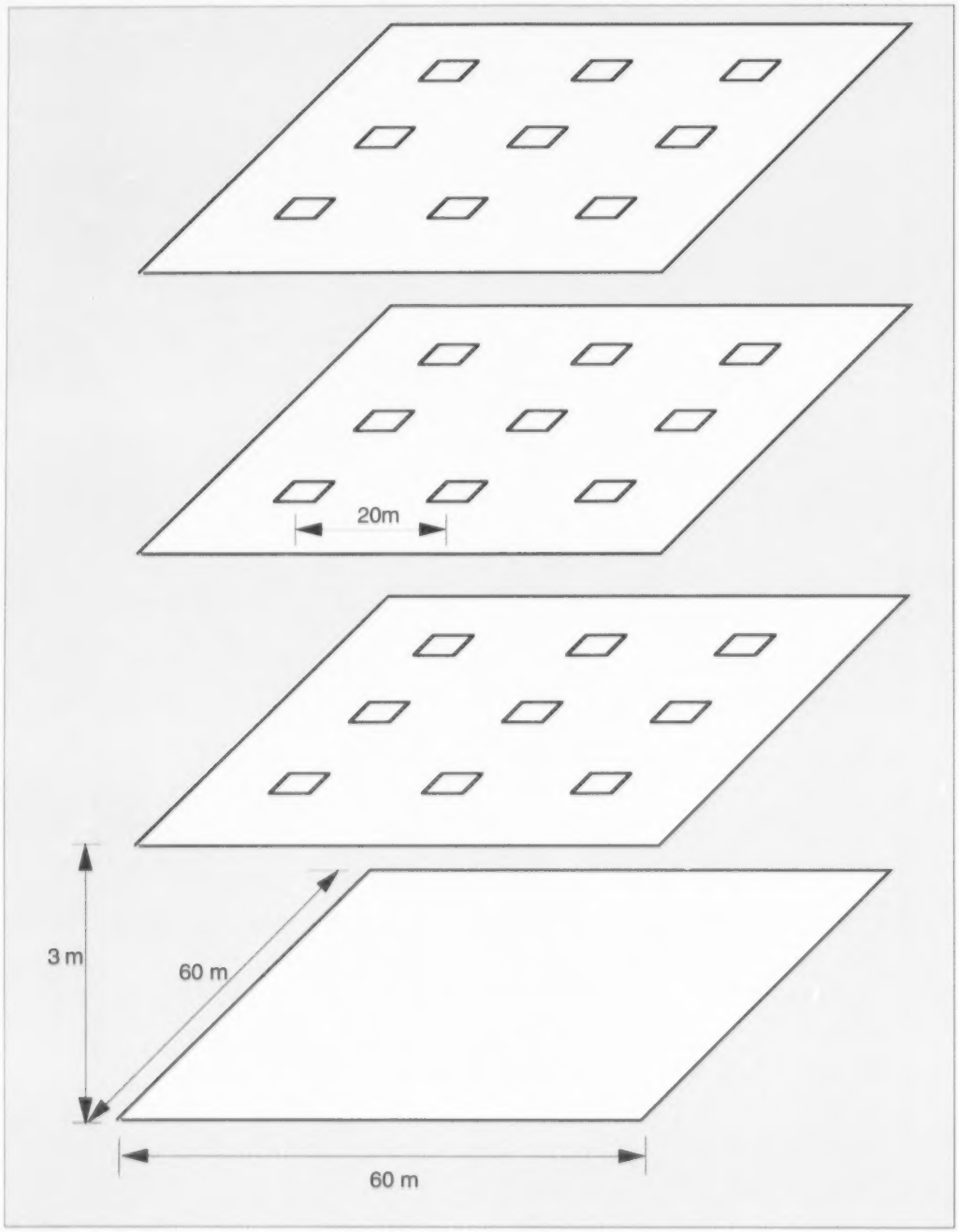

Figure 4. 10 Floor Plan for 9 Base Stations on every floor

when there are 12 base stations in the system. The time required for every iteration is proportional to n*m where, n is the number of base stations in the system, and m is the number of base stations used for each timing updating. Also, it is observed that as the system size increases the number of iterations required to reach the synchronous state also increases.

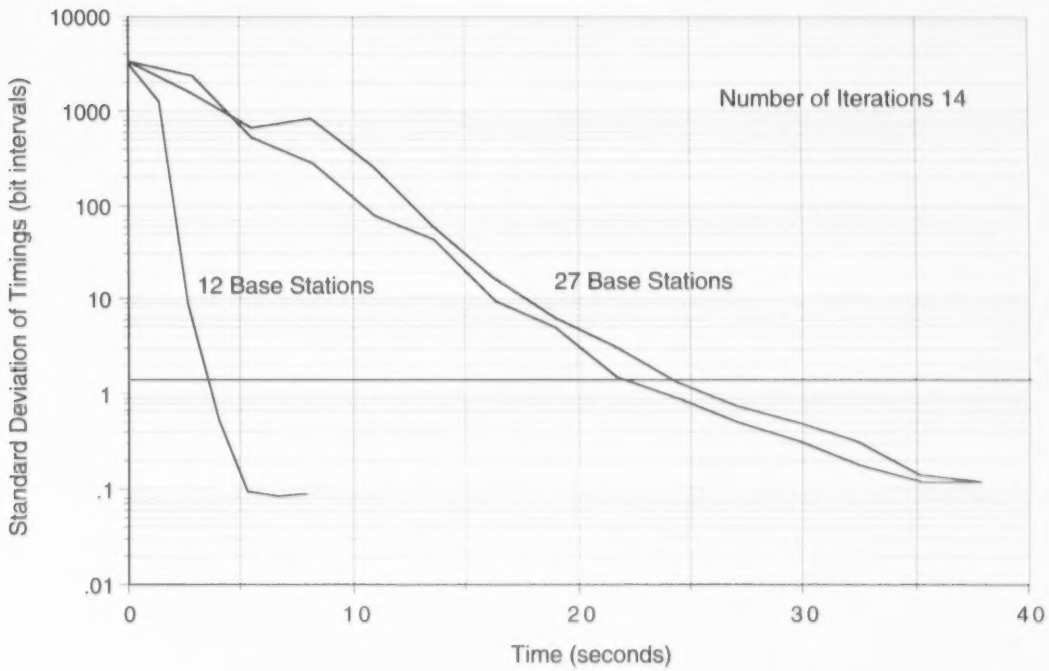

Figure 4.11 Effect of Size of the System

4.4.6 Effect of Adding a Base Station in the System

A situation may arise when a base station is put back into service after repair or a new base station is added to a synchronized system. To synchronize the newly added unsynchronized base station two approaches are considered:

1. Only the unsynchronized base station adjusts its timings.
2. Every base station in the system adjusts its timing to synchronize the system.

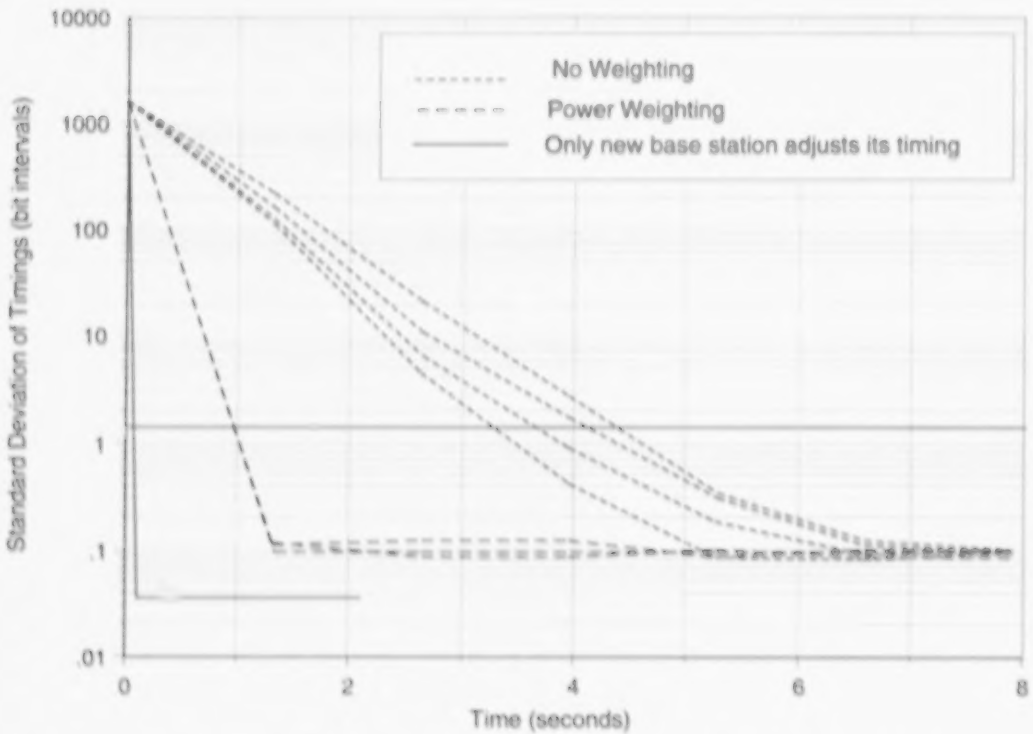

Figure 4.12 Effect of Adding One Base Station to the System

In the first approach the base station is synchronized after only its first timing update. As shown in Figure 4.12 the base station synchronizes in less than 0.15 s. For the second approach, when all of the base stations adjust their timings, the results are obtained for both the weighting strategies. The time taken to reach the time synchronous state, when the errors are weighted with power, is less than the time taken in other case. By weighting errors the with received power a base station adjusts its timing mainly based on the timings of the neighboring base stations. When initially only one base station is out of

synchronism, timings of the only those base stations which are closer to the unsynchronized base station are changed and they synchronize again to the rest of the system soon. But when no weighting is applied, even the distant base stations change their timings, i.e. the unsynchronized base station disturbs the timings of all of the base stations in the system and thus it takes longer time to synchronize again.

4.4.7 Effect of Multiple Independent System

In a multi-tenant environment it is possible that there are independent systems on the different floors of the building, which are installed at different times. Three independent systems are considered on the different floors of the building. Initially a four base station system is installed on the first floor. The base stations synchronize by measuring timing errors with respect to the other 3 base stations on the floor. As shown in Figure 4.13 the base stations takes between 0.3 to 0.45 seconds to synchronize. As there are only four base stations in the system, the time taken per iteration is very small.

The second system is assumed to be installed (on the second floor) later and the base stations in the second system synchronize to the system on first floor. Every base station in the second system (second floor) measures timing error with respect to other base stations on second and the base stations on first floor. This system synchronizes in about 0.2 seconds.

The third system is installed when the other two system in the building are working. To synchronize every base stations in the system monitors the

signal from rest of the base stations in the system. This system takes about 0.3 seconds to synchronize.

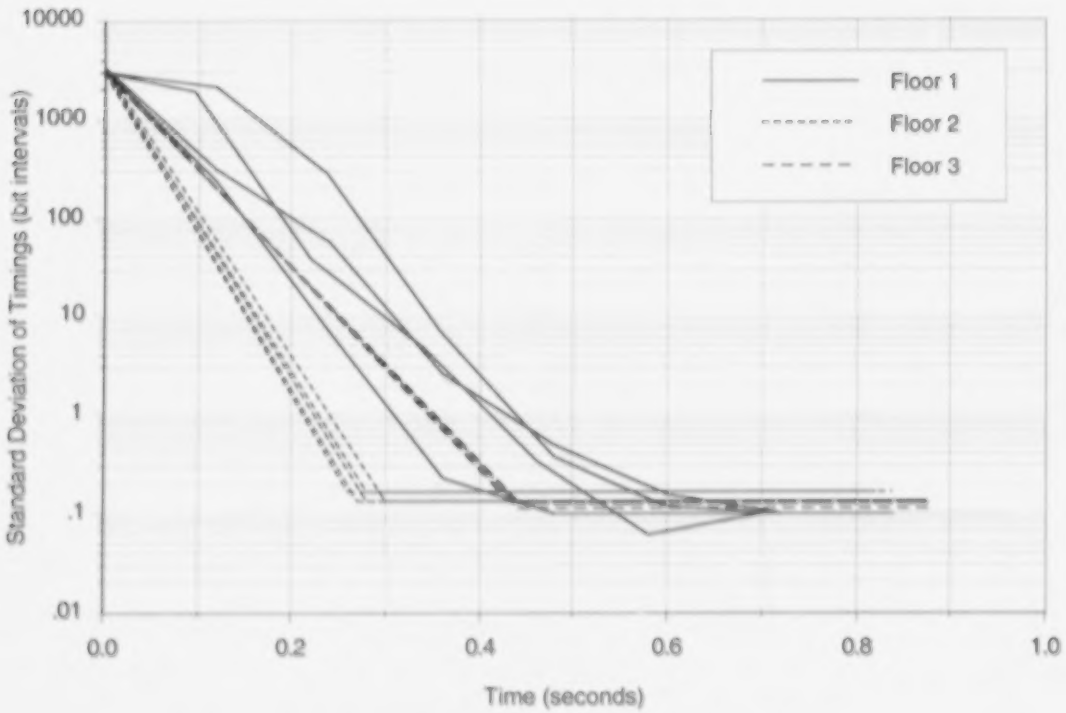

Figure 4.13 Effect of Multiple Independent System

If we have a single system in the building it is proposed that the base stations be synchronized floor by floor. In this case the total time taken by the system to synchronize is less than one second which is much faster than the normal sequential approach.

4.4.8 Simultaneous Updating at more than One Base Stations

As explained in section 2.2.2 in this approach the timings are updated simultaneously at a number of base stations. The results are obtained for

different initial conditions. As shown in Figure 4.14 there is no gain in the time taken to synchronize the system. This approach would require more information and more complex control mechanism at the central control unit, which may be difficult to implement as compared to the earlier approaches. Every time there are some changes in the system the corresponding changes would be required in the central control unit.

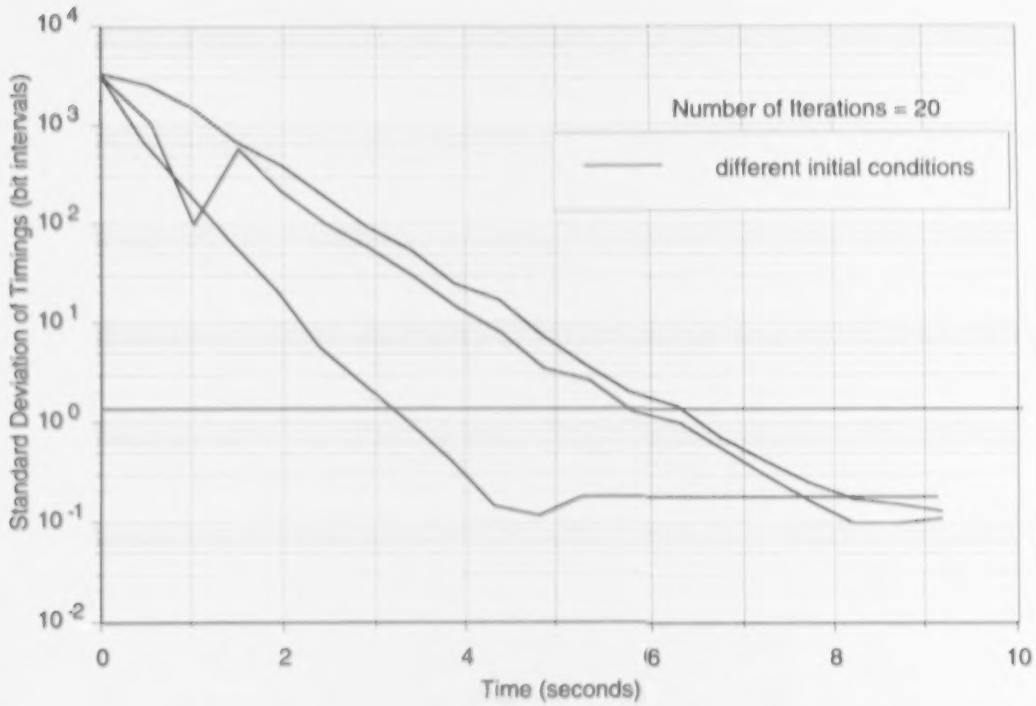

Figure 4.14 Simultaneous Updating at Number of Base Stations

4.5.9 Hierarchical Method.

Figure 4.15 shows the result for this approach. It took less than 2 seconds to synchronize the system. This is the fastest approach. This approach is, however, more complex than the earlier explained approaches because every base station is required to transmit its H value during the

synchronization process and the H value needs to be updated every time the base station adjusts its timing. Secondly, this system requires all the master base stations to be exactly synchronized before the synchronization process begins. If there is timing error between the master base stations this system would not work properly. An additional GPS receiver or other circuitry is required at every master base station in order to obtain a common timing reference.

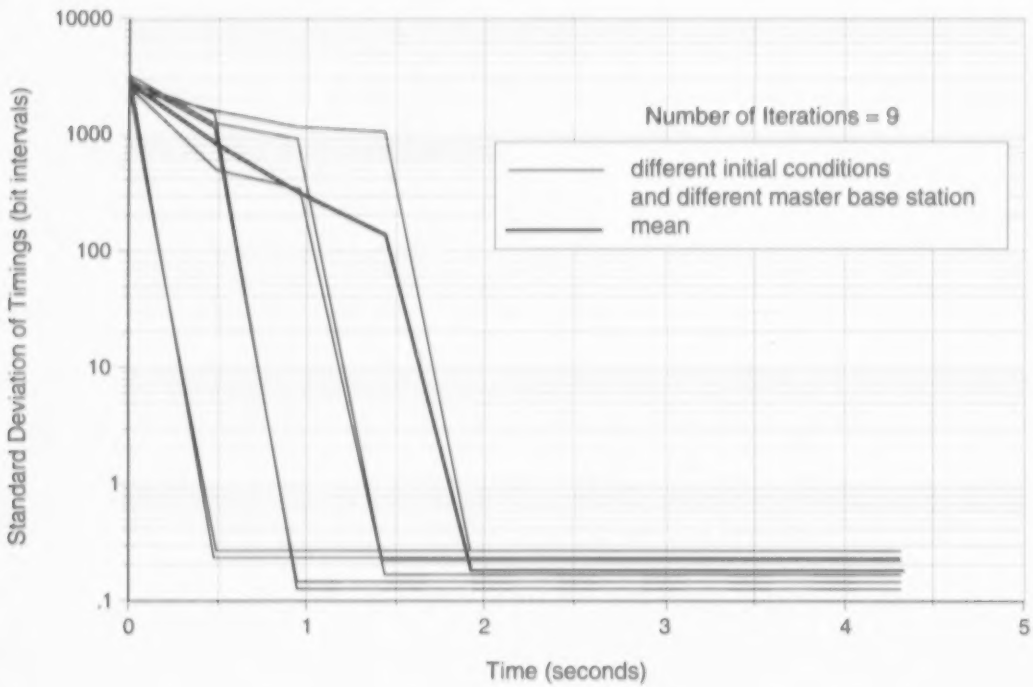

Figure 4.15 Hierarchical Method

Chapter 5

Conclusions

5.1 Introduction

The results obtained in this thesis are recapitulated in this chapter. Some of the implementation issues of over-the-air synchronization are also discussed and finally some recommendations for future work in this area are given.

5.2 Performance of Over-the-Air Synchronization Schemes

A flexible simulation model for the digital TDMA-TDD system has been developed in the C programming language. The structure of the system and its essential parameters have been chosen to comply with the DECT standard, however, the results are applicable to a wide class of TDMA systems. The proposed synchronization schemes have been evaluated in the indoor environment.

Two weighting strategies in the calculation of average timing errors have been evaluated. In one approach the timing errors are averaged with power as the weighting factor and in the other approach the timing errors are not weighted. The effect of the weighting strategies is determined for the sequential algorithm. The system reaches the synchronous state faster when the errors are weighted by power. In order to establish the stability of the sequential

synchronization algorithms, for both weighting strategies, the performance has been evaluated for a number of different sets of initial timings and environments. The system converges to a stable synchronous state in all cases.

The effects of other possible factors which could affect the performance of the sequential synchronization schemes have also been evaluated.

1. The effect of the order in which the base stations update their timings is determined. It is found that in a fixed order updating, the order of the timing update affects the time required to reach the synchronous state. But, if the base stations update their timings in random order on successive iterations, the time taken to synchronize the system increases. But this would allow autonomous synchronization with minimal central control and only the base station performing the measurement would have to be idled. In random updating, although every base station updates its timing once in every iteration, there is possibility that the timing at some of the base stations are updated twice without some other base stations updating their timings even once. This kind of procedure would slow down the synchronization process.

2. A partition on a floor severely attenuates the signals received from the base stations on the other side of the partition. This could affect the synchronization process. The over-the-air synchronization scheme has worked effectively in this situation, although it might take more time to synchronize when there are many partitions. Hence, this procedure is robust and able to compensate for variations in the propagation environment.

3. The time taken to attain the synchronous state is found to be dependent on the size of the system. The convergence time increases substantially in a larger system.

4. The time required to synchronize a new base station to an already synchronized system is also determined. Three different ways of synchronizing the new base station to the system are evaluated. In one case only the unsynchronized base station adjusts its timing and in the other two cases, all the base stations adjust their timings to synchronize the system. Synchronization is fastest when only the new base station updates its timing. When all the base stations update their timings to synchronize the system, the algorithm which weights timing errors with power synchronizes faster than the algorithm in which no weighting is applied. Hence, the best way to synchronize is to only update the timings of the unsynchronized base station.

In sequential synchronization algorithm only one base station updates its timing at a time. Synchronization algorithm in which a number of base stations update their timings simultaneously have also been evaluated. There is no gain in the time to synchronize the base stations in this case and this algorithm requires more centralized co-ordination, making the implementation difficult.

The hierarchical algorithm is a hybrid of over-the-air synchronization and the common timing reference schemes. In this approach the system attained the synchronization in minimum time. However, this method is comparatively much more complex to implement. First, all the base stations are required to transmit additional information about the H value. Secondly, if there is more than one master base stations in the system, it requires very accurate

synchronization of the master base stations at the beginning of the synchronization process.

In actual systems there is a possibility of errors in the measurement of the power and the timing. But, as the signal is demodulated for timing information. The error in the measurement of timings will be less than one bit interval. The DECT standards require that the power should be measured with an accuracy of 6 dB. As we have seen the power doesn't affect the performance significantly. Therefore, error in the measurement of power will not significantly affect the performance.

As the cell size is small the propagation delays are not signifiacant. So, the drift in the timings will be negligible.

5.3 Implementation Issues

In the proposed scheme the base stations being synchronized do not transmit while monitoring the signals from the other base stations. This can only be achieved when there are no portables communicating with the silent bases. Hence, the synchronization can not be performed continuously and it can only be performed at times when the system carries no or minimal traffic, e.g. at night.

The synchronization process needs to be coordinated from a central control unit. Hence there is a need for a protocol which would coordinate the synchronization process among the various base stations.

5.4 Recommendations for Future Work

There are aspects of over-the-air synchronization scheme which still need to be verified. We have assumed good connectivity between the base stations. Practically it might not be possible to demodulate the signals from all the other base stations in the system. Receiver sensitivity, co-channel and adjacent channel interference should be included in the simulation. Hence, there should be some way to report to the central control unit that the timing information is not available. There should be a procedure to deal with that kind of situation.

In the proposed scheme the base stations turn off their transmission while monitoring signals from other base stations. In TDMA-TDD systems the base stations transmit only in the active time slots, i.e. there is no transmission on the idle time slots. These idle slots could be used to monitor the signals from other base stations. In such a case there would be no need to turn off transmission and the base stations would be able to update their timings continuously.

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